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THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

Limitations of Computerized Lofting for Shell Plate Development

U.S. DEPARTMENT OF THE NAVY
CARDEROCK DIVISION,
NAVAL SURFACE WARFARE CENTER

in cooperation with
Newport News Shipbuilding

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REPORT

ON

LIMITATIONS OF COMPUTERIZED LOFTING

FOR

SHELL PLATE DEVELOPMENT

A Project of
The National Shipbuilding Research Program

for

The Society of Naval Architects and Marine Engineers
Ship Production Committee

Design/Production Integration Panel (SP-4)

PREPARED BY

Thomas Lamb
Director of Engineering
Textron Marine Systems
A Division of Textron Inc.

ACKNOWLEDGMENT

This report has been prepared by Thomas Lamb, but the material covered has been developed and prepared by a team of Computer Aided Lofting (CAL) developers and users. Thomas Lamb's contribution has been as coordinator of the study.

Without the participation of the following CAL developers there would have been no study

Albacore Research Limited
BMT ICONS Limited
Cali &Associates, Inc.
Coastdesign, Inc.
Kockums Computer Systems AB
Senermar

Their contributions, along with the contributions of Thomas Perrine of NASSCO, Shelby Anderson and Eddie Adler, as study consultants to Thomas Lamb, are acknowledged with appreciation. The study consultants ensured that the study met the project abstract goals and that the over-riding performance measurement for the study was the maximum use to shipbuilders. This was further attained by review of the study report by Bath Iron Works, Ingalls Shipbuilding National Steel Shipbuilding Company and Newport News Shipbuilding% and their efforts are also acknowledged.

The study was funded by the National Shipbuilding Research Program Design / Production Integration Panel (SP-4), chaired by R. Besselievre, of Ingalls Shipbuilding. The SP-4 Panel is one of the Ship Production Committee Panels of the Society of Naval Architects and Marine Engineers, which were established with the purpose of improving U. S. shipbuilding performance.

EXECUTIVE SUMMARY

Some shipyards are not satisfied with the current computer aided lofting (CAL) shell development systems that they use. This dissatisfaction manifests itself in fit up problems and the need for excess material (“green” or “stock”) to be left on some butts and seams to allow “corrections” to be made at erection.

Most shipbuilders desire a “cut to neat size” approach. This is obviously to eliminate labor intensive fitting cutting in and edge preparation for welding, on the assembly plattens or building berth.

On the other hand, most CAL developers recommend that stock material be left on one seam and one butt for each shell plate block with significant curvature. They claim that this is to take care of inaccuracies due to the platers’ skill level and limitations of the forming machinery, rather than inaccuracies in the shell development systems.

This study was undertaken to help put the shell plate development problems in their correct perspective and to determine if the shipbuilders’ goal of cutting all shell plates neat is reasonable.

The study was performed in two phases to suit funding restrictions. Phase I developed the Problem and Solution Description and Phase II covered the development of the Shell Plate Test Cases and the preparation of the Ship Designers’ Manual.

In order to better appreciate the description and discussion of the participating CAL developers’ systems, a historical background for CAL is presented. This includes a description of the traditional manual shell development methods and an example of their use for a typical simple shell plate. This enabled a comparison of the developed flat shape to be made and significant differences were found.

In addition, a description of a successful 1:10 scale shell plate development machine is presented. Its demise wass assured with the development of N/C burning machines and computer aided lofting.

In performing the study, it became clear that the problems were viewed differently by U.S. shipbuilders and the CAL Developers.

An attempt was made to obtain the views on this matter from three foreign shipyards, but all declined to participate.

All the participating CAL developers are aware of shell plate problems but they do not-see them as a limitation of the methods they use. They all point out that shell development of double curvature shell plates is an approximation. There is no exact “unwrapped” flat shape for such curved plates. However, they believe that the approximation gives developed flat shapes for plates that are well within current shipbuilding tolerances.

The aircraft industry has some problems that are similar to shipbuilding and others that are unique. As already reported, early aircraft Iofting used shipbuilding lofting techniques and Ioftsmen. Most existing aircraft manufacturers have their own computer aided lofting system. They have special attributes to handle their unique needs. The problems are handled by different approaches depending on need as follows

- Sheet stretching or hammer forming over dies
- Sheet shot peening
- Composite molds

Where plate development is performed it is done by multiple triangulation and stock is provided for fit up.

The six participating CAL developers can be grouped into two PC based and four main frame based systems. However, all the main frame based systems are currently offering stand alone and networked work station versions of their systems.

It should be obvious that a successful shell development system must be part of a total system that has a successful fairing system and experienced loftsmen/users to develop successful lines. Further, that the CAL fairings must produce fair and smooth hull surfaces with no bumps or hoIIows. However, this study assumes that this is the case and does not review or compare fairing systems.

All systems except Senermar’s FORAN use triangulation of many small panels formed by four 3-D space points to obtain the flat developed shape of the plate. Senermar use a unique approach of building up the surface definition for each plate from a number of analytical mathematical surfaces and then developing each one of the set of surfaces and nesting them together to obtain the flat developed shape of the plate. The SPADES system starts its development at one end of the plate whereas all the others start in the middle.

All systems except ShipCAM3 automatically take care of plate thickness and its location relative to the molded line.

All systems provide an N/C code output and a hard copy sketch of the developed plate and its marking. However, ShipCAM3 requires the use of an independent CAD system to accomplish this. They all provide manufacturing aid information. ShipCAM3, AutoSHIP and AUTOKON all offer different versions of plate strain information which can be used by the plate developer to help decide if developed plate is acceptable, and by the forming operator to show where the deforming force should be applied and to what extent

A number of attempts were made to get an aircraft company to participate in the study but to no avail.

In the Proposal and the Subcontractors' Technical Specifications for Phase I, five areas of a ship's hull that can be considered "problem" or "difficult" shell plates, from the point of view of successful CAL development, were identified. The six participating CAL developers then developed these identical shell plates representing the "difficult" areas. There is no intent to evaluate any of the development results. The resulting data is simply presented for review and use by interested readers.

Finally, a separate SHELL DEVELOPMENT GUIDE FOR SHIP DESIGNERS has been prepared and will be issued with the report It wilI also be made available to ship designers requesting it from-the SP-4 Panel Program Manager.

The project conclusions are

A. The shell development problems are viewed differently by shipbuilders and the CAL developers. This is surprising when it is remembered that computer aided lofting shell development methods have been in use for over 20 years. It would seem reasonable to expect developers and users (shipbuilders) to have worked together on the problems, or at least be in agreement as to what they are.

B. A review of papers by foreign shipbuilders covering computer aided shell development did not show the same concerns as some of the U.S. shipbuilders. Their message is that successful shell plate forming and erection is as much or more dependent on the material handling and forming equipment and the skills and training of the forming and erection workers as it is on the computer aided lofting method capability.

C. While improvements have been made to all of the CAL developers' shell deveIopment systems over the years of use, they have been in the user interface and to take advantage of computer improvements. None of the traditional CAL developers have incorporated major new techniques that significantly added to the accuracy of the developed plate flat shape. FORAN’S use of geometric surfaces patched into the flat plate is a different approach, as is the ShipCam and Autoship use of a finite eIement technique, but again it is not known if they improve on the triangulation accuracy.

D. The CAL systems are not “expert systems” nor do they incorporate “artificial intelligence”. This means that the use of the system, and specifically shell development, will be highly dependent not only on the experience the user has with the system but more importantly the user’s skill level and experience as a shipbuilding Ioftsman.

E. For most of the compound curvature shell plates on a ship’s hull, the accuracy of the shell development systems is well within normal shipbuilding tolerances.

F. The shipbuilders’ goal, to cut all shell plates neat, probably will not be realised in the foreseeable future. This is due to two facts, namely

1. It is mathematically impossible to develop an exact flat pattern for any plate with compound curvature.
2. Shipbuilding plate forming tools and operator skills do not have the required consistent and repeatable accuracy.

G. The development of the same plate by different CAL systems is not consistent even for the simpler test plates. The differences get significantly worse as the plate complexity increases. However, the consistency can be improved by dividing the complex shell plates into a number of smaller plates.

H. It is recognized that it is not the inconsistency between different CAL systems that is of importance to the shipbuilders who use the systems, even though it supports their concern as to the acceptability of current systems. They are more interested in the good fit up from adjacent plate to plate developed by the same CAL system, after cutting and forming. This study did not address this matter. To do so would have required groups of pIates in each test area to be developed and then to have actually cut, formed and connected the plates. This was not within the scope of the study.

The project recommendations are that

A. A study be undertaken of shipbuilding forming methods and the application of accuracy control to improve shell plate forming accuracy and consistency.

B. A study be undertaken to develop ways to use advanced measuring devices, such as laser theodilites, for the checking and control of shaped shell plate forming.

C. Shipbuilders and CAL developers work together to develop new and improved computer developed data to assist shell plate forming operators to attain better accuracy and consistency

D. A study be undertaken to physically match a number of adjacent shell plates on an actual block for plates developed by a number of the CAL developers involved in this project, to determine fit up accuracy or lack thereof, as discussed in 8.1 H above. This would obviously have to be performed by a shipbuilder with the capability to cut and form the shell plates involved and to assembIy them on a jig. The shipbuilder must have the capability to accurately measure the cutting forming and fit up of the shell plates before joining as well as the overall final panel accuracy after joining the individual shell plates.

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1.0 INTRODUCTION

1.1 General

Computer aided shell plate development methods have been around for approximately 30 years. At first the computer approaches simply duplicated the traditional manual ship lofting approaches. In fact, early versions of computer aided lofting systems emphasized this as an advantage, in the hope that the traditional Iofstmen would be more willing to accept the “new” tool if they knew it emulated how they manually performed the same task.

The demand for improved accuracy, plus the evolving capabilities of computers and software, resulted in irnproments to all the areas of computer aided lofting including shell plate development

Unfortunately, even with these improvements, most shipbuilders are still dissatisfied with the accuracy of the current computer shell plate development The shipbuilders’ goal is to cut every shell plate neat (with no excess material around the developed shape to allow for the inaccuracies at fit up). More specifically,they want to be able to erect a block to another block with the erection joints matching perfectly, thus minimizing rework at the erection stage. Most shipbuilders report that they cannot do this for shell plates with any shape other than simple curvature in the transverse direction, which can be simply rolled.

Fit up is a very labor-intensive task which is subject to human error. Even with block construction and only fitting and cutting one seam and one butt for the block, it is still very labor intensive.

The computer aided lofting developers and users claim that it is not the development inaccuracies that cause the problem and resulting need for excess material (stock or green material) but rather the shell plate processing and forming skill level and equipment used.

To help put the shell plate development problems in their correct perspective and to attempt to determine if the goal of cutting all shell plates neat is reasonable, this study was undertaken. It was performed in two phases.

Phase I objectives were

- To obtain the participation of existing shipbuilding and aerospace computer aided lofting system developers/users to discuss
  - Shell development problems
  - The methods they use to develop shell plate and handle the problems
  - Any stipulated limitations in application

- To report on the findings of the above discussion

- To select five (5) shell plates representative of the “difficult’’type as test cases to be developed by the computer aided lofting system participants, in Phase II of the study.

Phase II objectives were:

The development of the 5 test cases by each of the participating CAL subcontractor

Comparison of the developments and presentation of the findings

Preparation of a guideline for ship designers to use for hull shaping and shell plate selection that assists in their-accurate fabrication

This report covers both phases. A separate SHELL DEVELOPMENT GUIDE FOR SHIP DESIGNERS achieves the final project objective.

1.2 Background

The development of the shell plates of a ship has been a necessary shipbuilding skill since the introduction of iron ships. Early shipwrights/platers did not develop shell plates. The loftsmen laid the lines of the frames on the screive board. Templates were then made for each frame from the frame lines on the screive board. The actual frames were then shaped to the templates. Once the frames were erected and secured by the deck beams and ribbands, the shell plates were “lifted off” the frames by wood strip templates (patterns). The template was used to transfer the flat shape to the plate which was marked and then cut As the seams and butts were either lapped or strapped and riveted, accuracy was not as essential as it became for welded ships and is today for modern shipbuilding methods. Also the shape of the shell plates was kept as simple as possible by following the “natural” straking for the hull shape.

As can be well imagined this approach was very labor intensive. The practice of lofting and shell plate development from the full scale frame body plan on the loft floor was a natural development in the progress of shipbuilding technology at that time.

There are only a few well known and well used manual methods for shell plate development Three of them are traditional, namely

- Girth Line
- Squaring Off
- Triangulation

A more recent (1954) method is based on the concept of a Geodetic Line.

Squaring off and triangulation methods can be either edge or center based, whereas the geodetic line method is only a center approach.

The first attempt to improve on the full scale lofting approach was the fairing of ship's lines by the method of differences. This was a manual calculation approach that improved on the time taken to fair lines, but it was still labor intensive and required a higher level of educated technicians to apply it Once the fairing was complete it was still necessary to lay down the frame lines on the Ioft floor and the development of shelI plates and frame templates were lifted in the traditional manner.

The first major break from the traditional loft and lofting was the 1:10 scale lofting developed in Germany by Sicomat in the late 1950's. Some developments based on this approach were the opticaI projection of the 1:10 drawing to full scale on the plate for marking and the electronic optical following controller that could direct the burning machine.

The manual development of shell plating required skilled and experienced loftsmen. In an attempt to improve on the manual method and to reduce the dependence on skilled loftsmen, the G.A.G. PLATE DEVELOPMENT JIG was developed in Germany in the early 1960's. It was a logical development in parallel with the 1:10 lofting and burning machines. Many U.S. shipyards purchased such machines and used them until they changed to computer aided lofting. In some cases this was well into the late 1970's. Figure 1.2.1 shows a schematic for the machine and Figure 1.2.2 a photograph. It was operated by setting sliding frames 4/5 at ship frame locations. Hardened steel insulated points on the upper rod 6 were positioned in a special guide frame 10 for each ship frame by laying the special frame on the body plan. The flexible plastic battens on the lower rod 6 were then fitted to the hardened steel points. This was done for alI ship frames necessary to cover the shelI plate. In the original application special foil backed paper was used to obtain the shell plate. This was fed into the space between the points and the battens. The lower rod was then raised until it forced the paper into contact with the points. Then an electric current was passed through the jig and small holes were burned into the foil backed paper. The paper was then removed from the machine and Iaid out flat Lines were faired through the small hole marks to obtain the boundaries of the plate and any marking curves that had been modelled. One U.S. shipyard did not use the electric current marking but simply used the sharp hardened steel points to prick holes in thick mylar'. In both cases 1:10 shell plate mylar templates were then generated from the jig template and used to mark and burn the shell plates. Most shipyards that used the machine report general satisfaction with the approach, but it became obsolete with the desire and capability to mark and bum shell pIates on N/C machines and the development of acceptable computer aided lofting shell development.

About the time that the optical tracing 1:10 system was being put into practice, a number of organizations/countries were developing computer aided lofting (CAL) systems, and also computer or numerical controlled burning and marking machines.

While the British and the Scandinavians were the most successful in putting CAL into practice, in the early 1960's, the U.S. did experiment with numerical controlled (N/C) burning machines at the Todd shipyard in Seattle under a MarAd funded study. Unfortunately for the U.S., nothing came of it

The British system was developed by the British Ship Research Association (BSRA), which was jointly funded by the major British shipbuilders with significant support from the British government Their charter was to develop systems that would give the British shipyards a competitive advantage through technology, so there was no interest to expand the use of BSRA systems in other countries. In fact the opposite was the case.

On the other hand, both the Norwegian AUTOKON and the Swedish STEERBEAR systems were marketed aggressively around the world. AUTOKON was marketed in the U.S. by COM/CODE Corporation, who had obtained the Iicence for it in the U.S. and Canada COM/CODE licenced AUTOKON to Newport News in 1972 and in 1973 gave a special Iicence to MarAd, who, in turn, could Iicence up to ten individual U.S. shipbuilders. However, the anticipated number of shipyards did not purchase the AUTOKON licenses, perhaps because the decline in U.S. commercial shipbuilding had already started.

General Dynamics had been a user of the AUTOKON system before COM/CODE obtained their Iicence and continued to use it

Bethlehem Steel shipyard installed an N/C burning and marking machine in 1966 and tried to develop its own system but was unsuccessful. In 1974 it joined the MarAd sponsored AUTOKON users' group.

Avondale shipyard developed its own system, under the direction of Fil Cali, which eventually developed into the SPADES system currently used by Avondale, Ingalls, Marinette Marine, NASSCO, Lockheed (before it closed) and many other shipyards through subcontracting CAL service from Cali & Associates, Inc.

Since then the different CAL systems have became more user friendly, efficient, integrated and capable of providing more shipbuilding oriented user data. With the exception of FORAN, which developed as a design system then added lofting, these systems were first developed as a computer aided manufacturing (CAM) tool. Over the years they have been extended back into design and planning to offer a "total shipbuilding system."

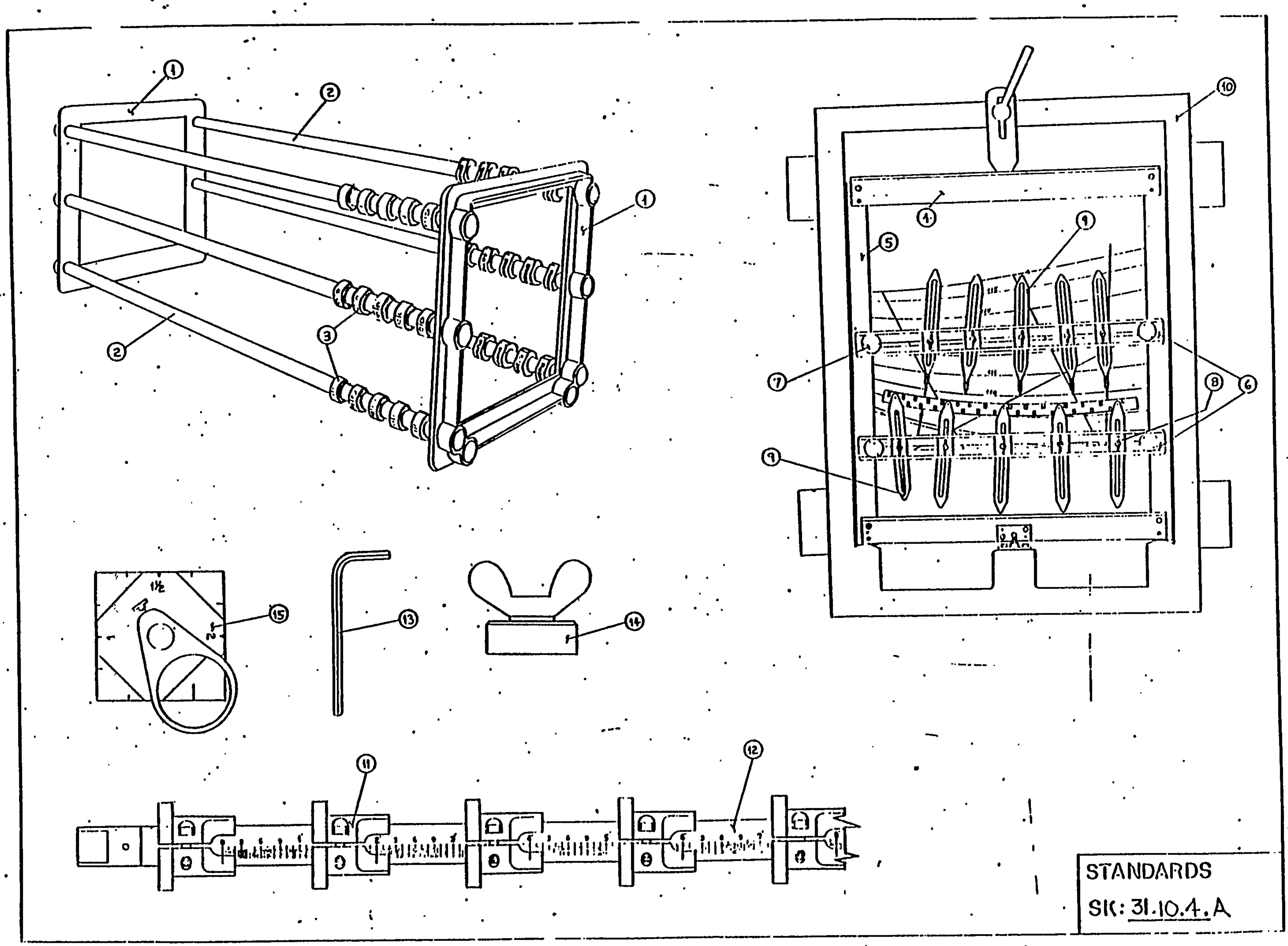


FIGURE 1.2.1 - G.A.G. PLATE DEVLOPMENT JIG SCHEMATIC

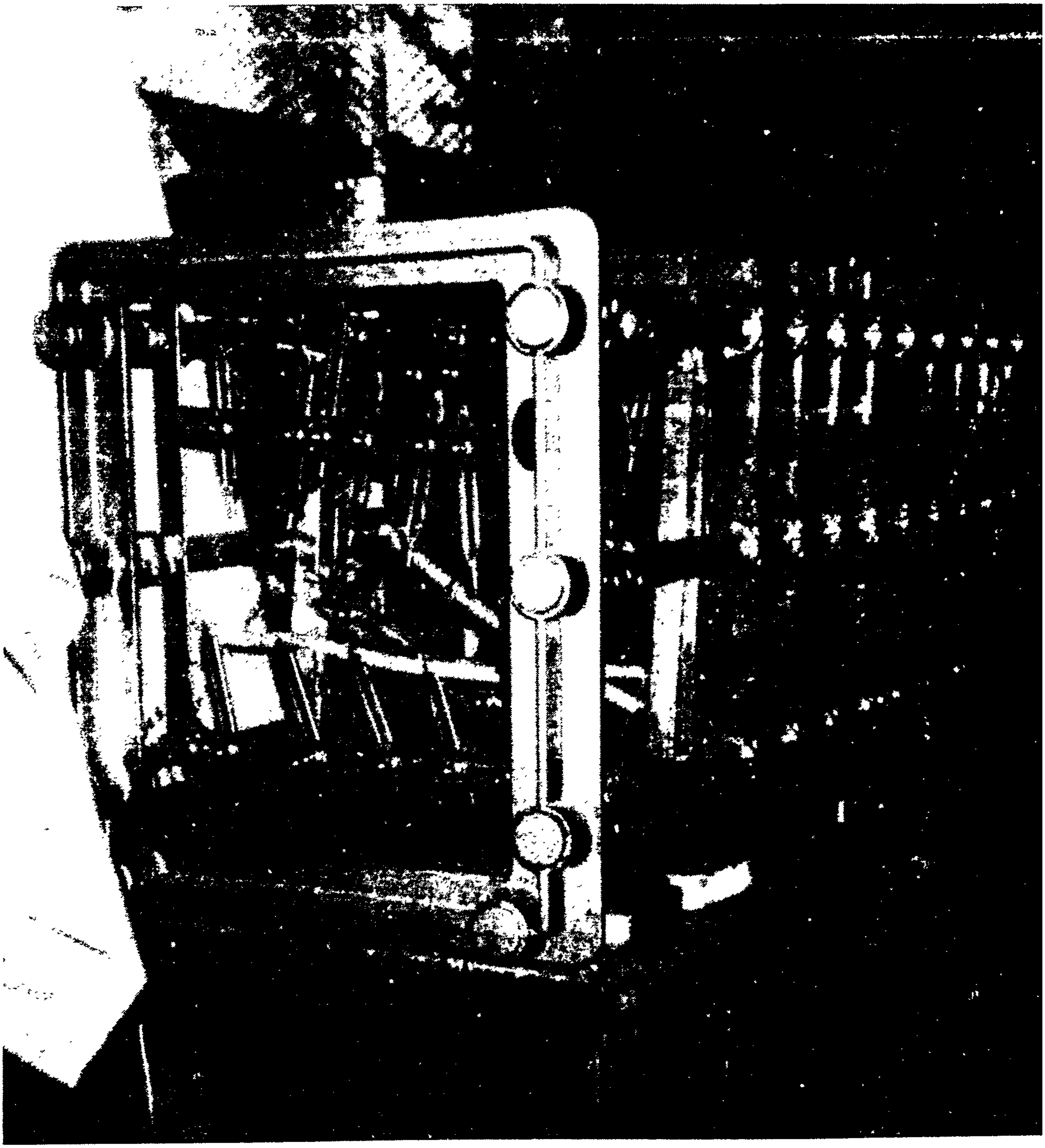


FIGURE 1.2.2 - G.A.G. PLATE DEVLOPMENT JIG

Lofting methods developed for steel shipbuilding were used by the early aircraft manufacturers. Both Both Boeing .and McDonnel Douglas later developed their own CAL systems. Both of these systems have been used for ship lofting and shell plate development, but the results have been no better than that offered by the shipbuilding CAL systems.

In the last decade, simpler and lower cost systems for ship lofting have been developed with the aid of the personal computer. While they do not offer all the capabilities of the established total shipbuilding systems, they do offer a lower cost alternative way for a shipbuilder to obtain a CAL and N/C generating capability.

Today, some shipbuilders still believe that there are definite limitations to the use of computer aided shell development systems. For example, the plates for the lower bottom of the bulbous bow of a U.S. aircraft carrier, which was damaged in a collision with an underwater object, was considered undevelopable. A full scale shape set (mock up) of the damaged area had to be built and the plates lifted off by full scale wood strip templates in the traditional manual way. Also, blocks in the modem modular shipbuilding approach are designed with transverse/verticaI butts and horizontal joining seams. This results in the joining plate having significant twist and backset in certain parts of the forward and aft lower shoulders. Some recent blocks have been out of alignment by 2 to 3 inches at the comers of the block.

Some U.S. shipbuilders claim that the Japanese shipbuilders cut all plates neat and all blocks without stock, and they fit! However, at the 1992 NSRP Symposium it was reported (1) that a major Japanese shipbuilding group were currently far from achieving this goal. 16 to 30% of their formed shell plates required back stripping or cutting and they always leave stock on bow and stem blocks. This is not too different from U.S. shipyard practice. Another Japanese shipbuilder is reported to leave only 1/4 inch when stock is required and if it fits well when erected to the adjacent block it is simply left on. Otherwise it is used for fit-up adjustment

Most CAL system developers recommend that stock material be left on one seam and one butt for each block with significant curvature. Many say this is to take care of inaccuracies due to the platers' skill level and limitations of the forming machinery, rather than inaccuracies in the plate development Today, most shipbuilders desire a "cut to neat size" approach. This is obviously to eliminate labor intensive fitting cutting in and edge preparation on the building berth or plattens. However, it appears unattainable. Why is this so? This study was performed to attempt to answer this question.

(1) - See 9.0 References

1.3 Project Team

With the objective to obtain the input of as many CAL developers and users as possible, the project team had to include the developers of the most successful existing CAL systems. The following list of CAL developers that participated on the team shows that this was accomplished.

Albacore Research Limited
BMT ICoNS Limited
Cali & Associates, Inc.
Coastdesign, Inc.
Kockums Computer Systems AB
Senermar

Participation of a U.S. aircraft lofting system developer proved to be more difficult Boeing Aircraft Company provided a brief description of their current approaches and advised that they are still looking for better ways to accomplish aircraft skin plate development McDonnel Douglas, even though they still offer their system for sale or use to shipbuilders, and it was in use in the Philadelphia Navy Yard, did not follow through on their initial indication of interest in participating.

Attempts to get British Aerospace, Boeing Aircraft Company (second try) and Lockheed also failed. Therefore this goal was not achieved.

Three shipbuilding/lofting consultants were also sequestered onto the team, namely T. Perrine, S. Anderson and E. Adler. Their function was to provide an overall review/control on the study process and progress to ensure that it followed the Project Abstract and was relevant to the shipbuilders' needs.

This latter task was also monitored and influenced by obtaining the participation of Bath Iron Works, NASSCO and Ingalls Shipbuilding as reviewers of the draft report

Finally, Thomas Lamb rounded out the project team as the study coordinator and preparer of this report

1.4 Shell Plate Development Traditional Manual Methods

1.4.1 Introduction

The first method that was probably used to attempt to develop shell plates, rather than lifting them off the erected frames, is similar to what is called today the Girth Method or Straight Line Method. It is still used today for relatively simple plates with only curvature in the transverse direction and no back set in the plate.

Another early approach was the Edge Squaring Off method. This method proved to lack the accuracy desired, in that developments using upper and lower seams as the "set of"f curve provided different developed shapes.

To overcome this limitation, squaring off along the middle of the plate was introduced.

Others approached the quest for accuracy by conceiving completely different methods. One such method was triangulation. Again, it first was based on a single expanded seam but the accuracy was still not satisfactory. Therefore a middle or center double triangulation method was tried and proved acceptable for most of the curved plates.

In Japan, a method similar to the center squaring off method was developed. However, instead of measuring girths along the frame lines from the mean line between adjacent squaring off lines, they are measured from the intersection of the frames and a specially developed curve called a "Geodetic Line." This curve has the property that when expanded onto the flat plate, it is a straight line.

"Difiicult" shell plates still had to be templated from full size built up frame sets.

In order to appreciate the discussion of shell plate development problems and the methods used by the computer aided lofting system developers, a more detailed description of the above traditional manual methods will be given. As can be imagined, there are many variations of the methods and the following descriptions are only to give an appreciation of each method, not a detailed expose of all the refinements and adaptations.

A common shell plate will be used to show how each method was applied and also to compare the manually developed shape from each method.

1.4.2 Girth (Straight Line) Method

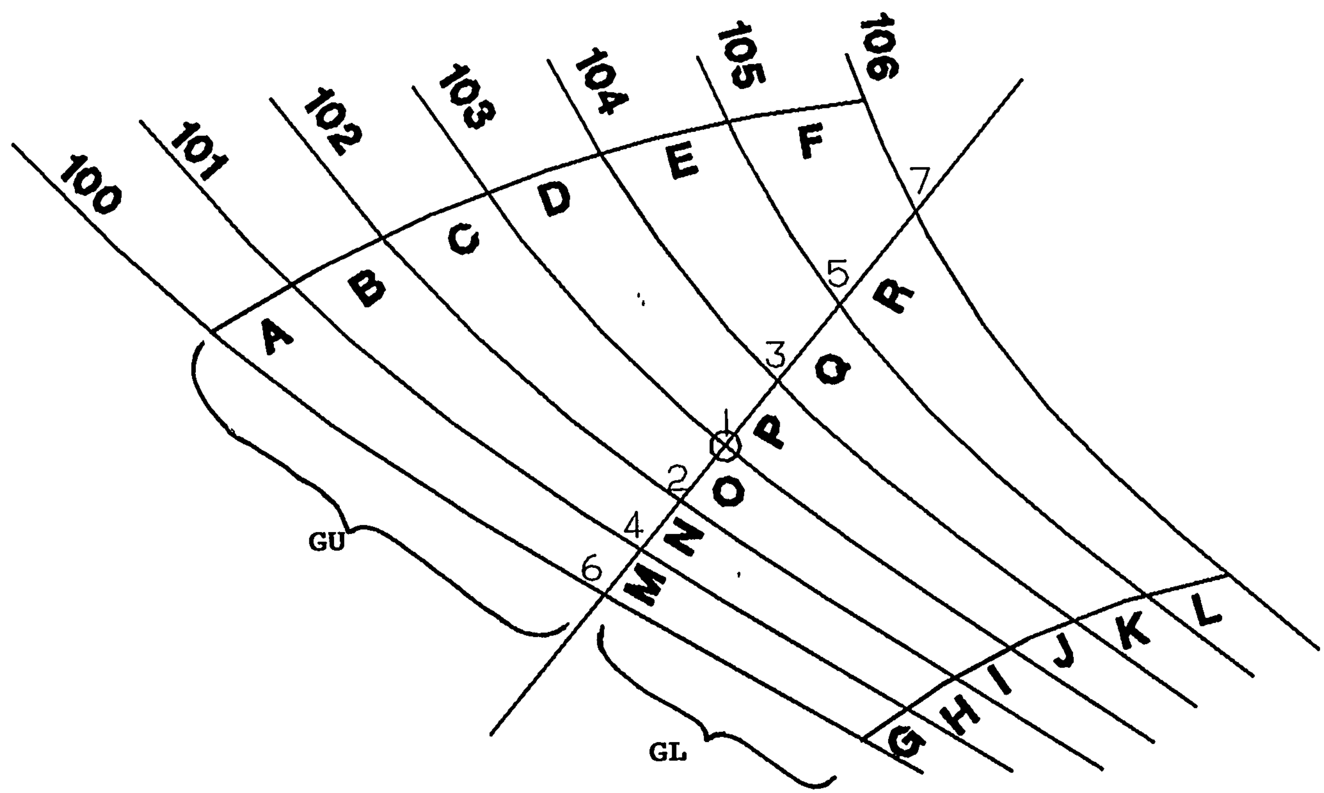
The Girth Method is simple to use. Figure 1.4.2.1 shows a typical shell plate on the body plan. To develop a flat shape for the shell plate, a point 1 is selected on a frame near the middle of the plate length. A straight line is drawn normal to the frame through point 1

It is then necessary to “expand” the lengths of the straight line and the upper and lower seams. Figure 1.4.2.2 shows how this is done, by drawing a frame spacing grid and setting off the distances, such as A, B, C, D, E, F, G, H, I, J K, L and M,N,O,P,Q,R. A curve is drawn through the points on each frame line and the “expanded” distances, such as A’,B’,C’,D’,E’,F; etc. are determined for the upper and lower seams and the straight line.

The girth lengths from the straight line intersection points on each frame to the upper seam, GU and to the lower seam GL are lifted off the body plan.

The developed shape of the shell plate is determined as follows and shown in Figure 1.4.2.3

1. Draw a straight horizontal line.
2. Establish point 1 at its middle and set off points 2 to 7 using expanded distances between points on line.
3. Draw a line through point 1 normal to the horizontal line.
4. Set of girth lengths GU103 and GL103 to establish the upper and lower seam intersection points on frame 103.
5. Determine upper seam intersection point on frame 102 by drawing arcs of radius equal to C’ from the upper seam point for frame 103 and equal to GU102 from point 2 on the horizontal line.
6. Repeat 5) for upper and lower seam frame intersection points for all frames.
7. Draw curves through upper and lower seam points.



GIRTH (STRAIGHT LINE) METHOD

FIGURE 1.4.2.1 - SHELL PLATE BODY PLAN

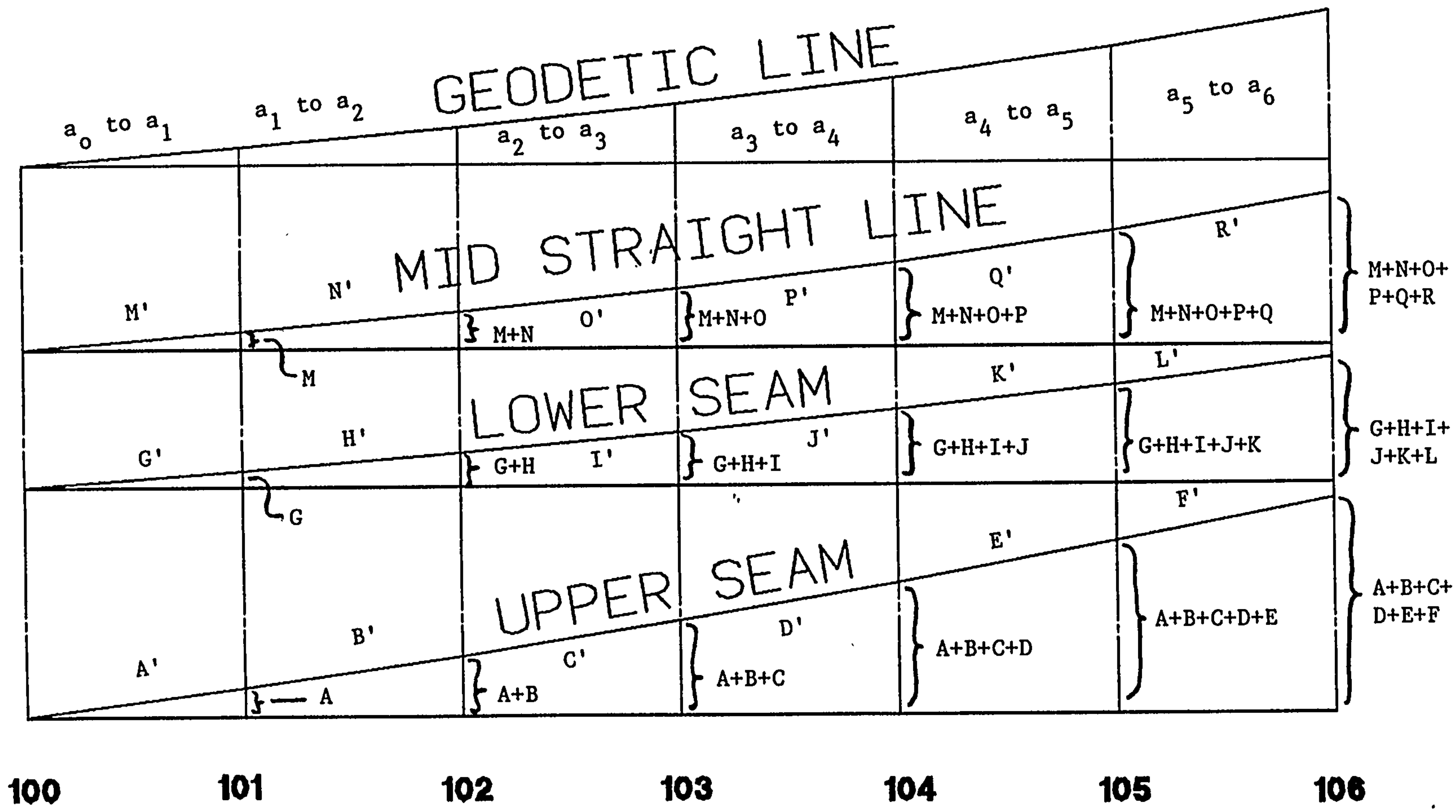


FIGURE 1.4.2.2 - SEAM AND LINE EXPANSIONS

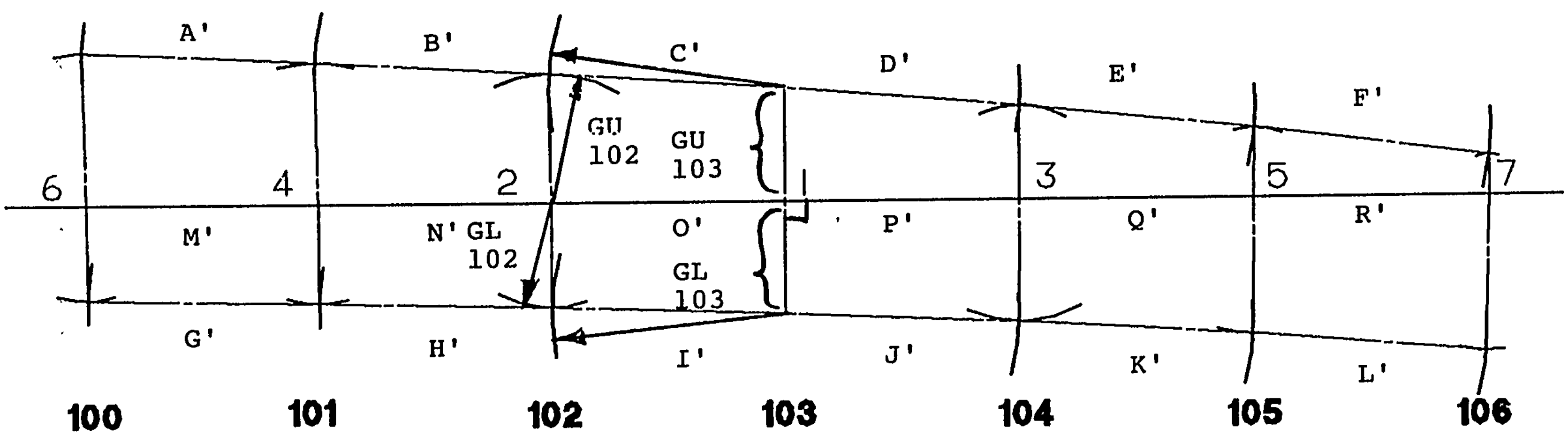


FIGURE 1.4.2.3 - GIRTH (STRAIGHT LINE) METHOD SHELL PLATE EXPANSION

1.4.3 Edge Squaring Off Method

The Edge Squaring Off Method was a popular method for early Ioftsmen as it was relatively simple.

The method will be performed using both the upper and lower seams in order to determine if this will result in any difference in developed shapes.

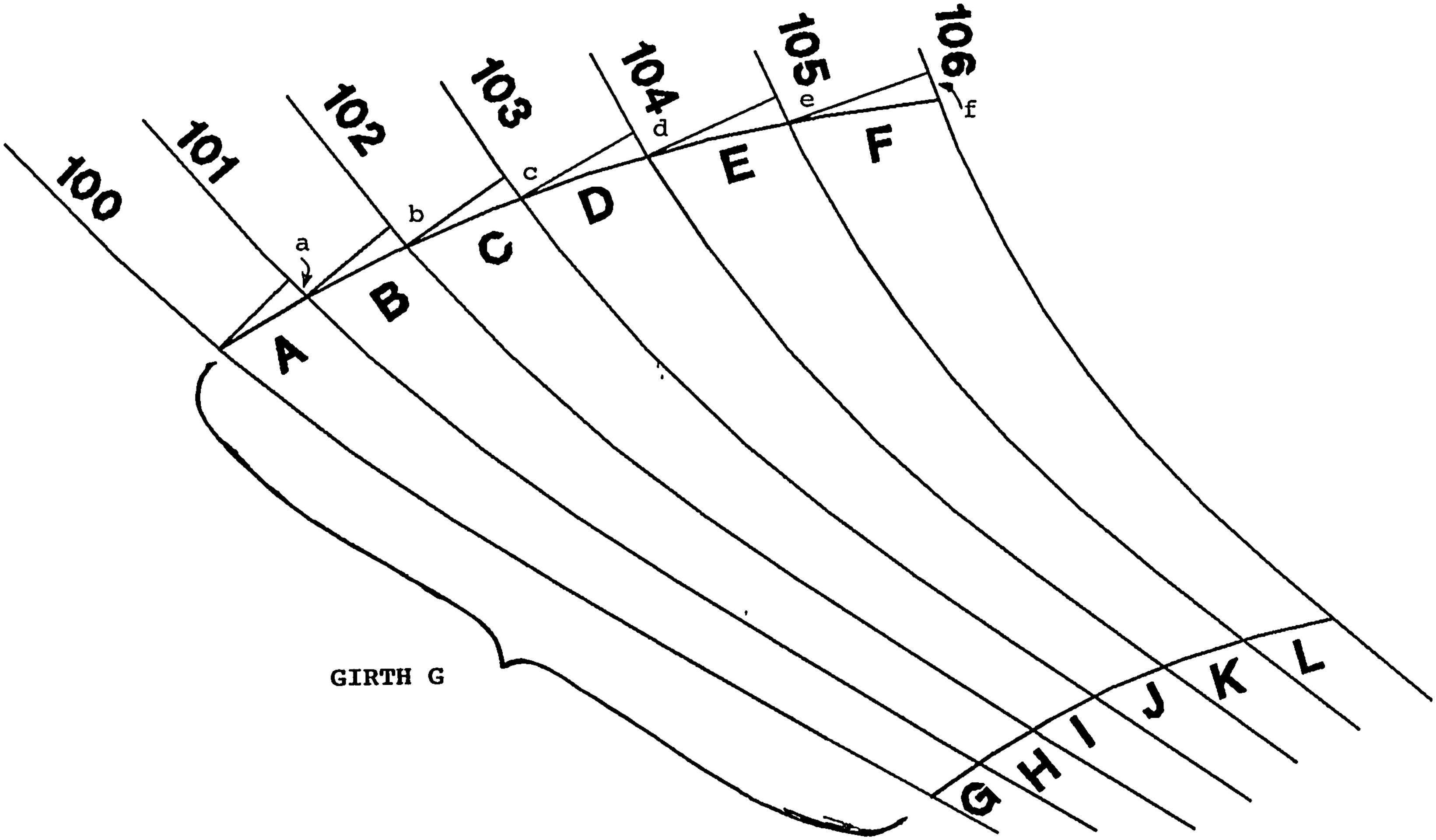
First it will be described for the upper seam and only the developed shape will be shown for the lower seam.

Figure 1.4.3.1 again shows the shell plate on the body plan.

The upper and lower seam distances between frames are expanded as described for the Girth Method. On the body plan, starting at frame 100, a line is drawn normal to frame 101 passing through the intersection point of the upper seam and frame 100. The distance that this normal line intersection point on frame 101 is above or below the seam / frarne intersection point is designated a This is repeated for frames 102 through 106 to determine b, c d, e and f. These differences are the "squaring off' distances. The girth lengths, from seam to seam, are lifted off the body plan for each frame. This provides all the information required to develop the flat shape of the shell plate. In actual fact only the seams of the developed shape will be drawn. The butts require a little more measuring to establish the "bow" of the frames on the developed shell plate. However, this is not important to the objective of this description.

The seams of the developed shape are determined as follows and shown in Figure 1.4.3.2:

1. Draw a vertical line equal to the girth length G1OO.
2. Draw a line normal to this line at its upper seam intersection point
3. Draw an arc of radius A'.
4. Draw a line parallel to the normal line a distance of a from it
5. The intersection of the parallel line and the arc is the point on the upper seam at frame 101.
6. Draw an arc of radius the girth length, G101, from the upper seam point determined in 5).
7. Draw an arc of radius G' from the lower seam point on frame 100.
8. The intersection of the arcs for 6) and 7) gives the lower seam / frame 101 intersection point
9. Repeat steps 3) through 8) for frames 101 through 105 using corresponding expanded seam distances, squaring off distances and girth lengths.
10. Draw curves through upper and lower seam points.



EDGE SQUARING OFF METHOD

UPPER SEAM

FIGURE 1.4.3.1 - SHELL PLATE BODY PLAN

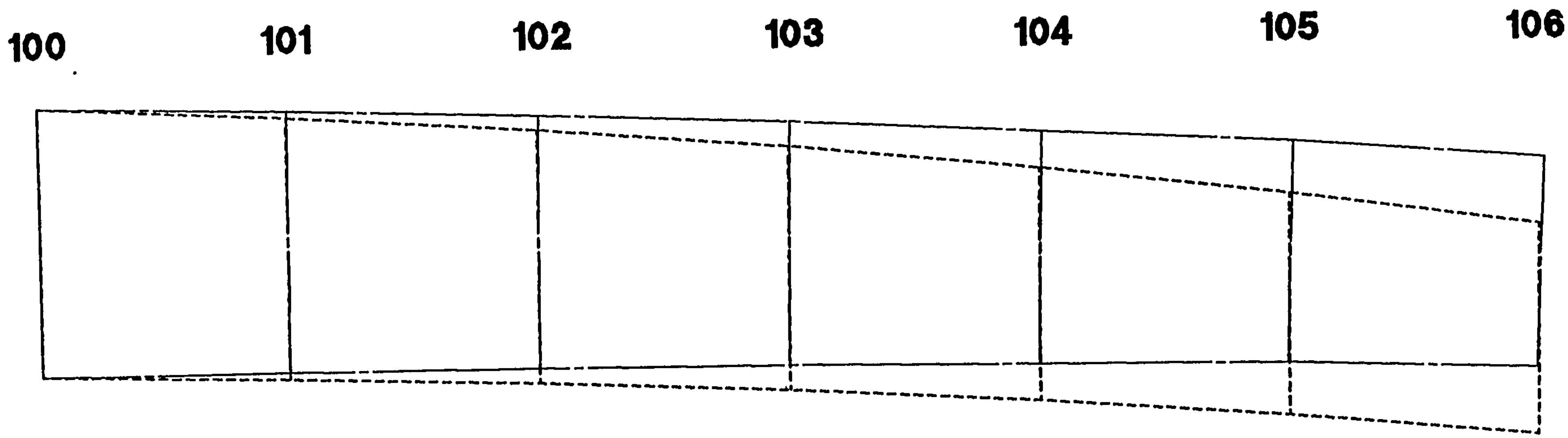


FIGURE 1.4.3.3 - COMPARISON OF UPPER AND LOWER SEAM SHELL PLATE EXPANSIONS

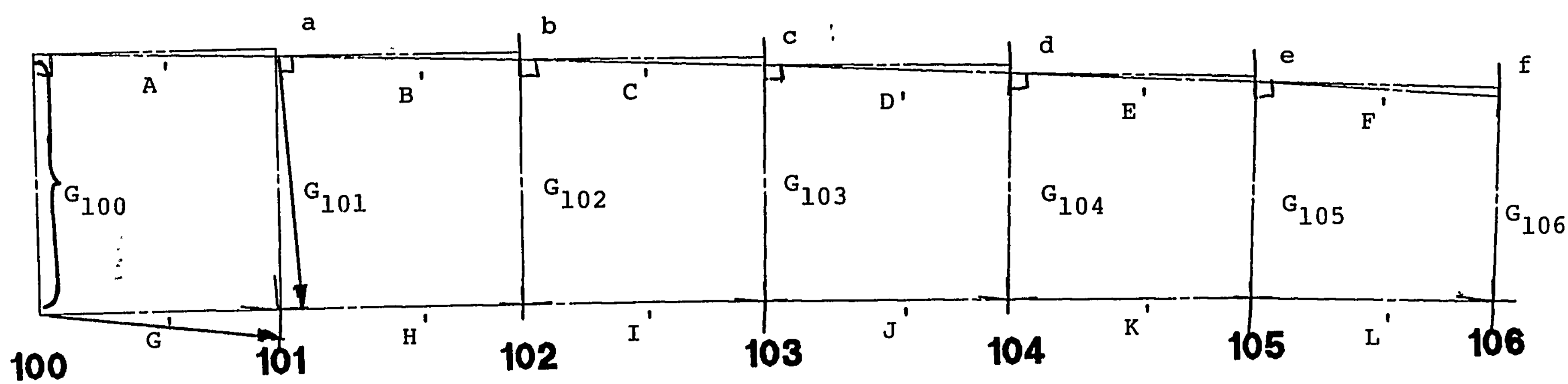


FIGURE 1.4.3.2 - EDGE SQUARING OFF METHOD SHELL PLATE EXPANSION

Figure 1.4.3.3 shows the developed shapes for both the upper and lower seam squaring off cases, overlayed on each other. As can be seen, there is a significant difference (12.75 inches at the upper comer of frame 106).

It is easy to see how this "inaccuracy" could have serious impact on fit up of a shell plate to adjacent shell plates.

1.4.4 Center Squaring Off Method

The Center Squaring Off Method was developed to eliminate the inaccuracy of the edge squaring off method. Again, Figure 1.4.4.1 shows the shell plate on the body plan. The upper and lower seams are expanded to determine distances A' through L'.

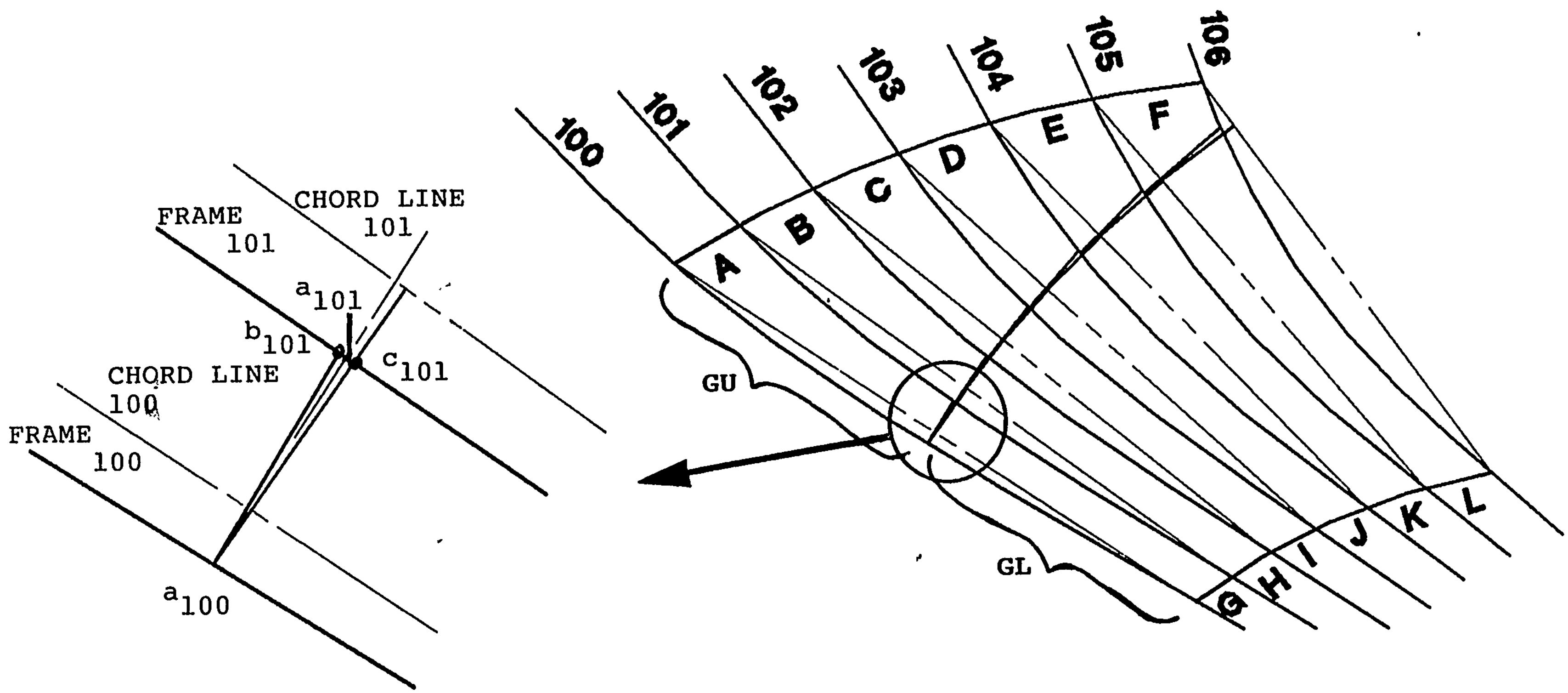
At each frame, on the body plan, chords are drawn connecting upper and lower seam / frame intersection points. On frame 100 select a point a100 on the frame near the middle. Draw a line from a100 normal to the frame 100 chord line until it intersects frame 101 and designate this point blO1. Draw another line from a100 normal to frame 101 chord line and designate the intersection of this line with frame 101, c101. Establish a point al0l equidistant between bl0l and c101.

Repeat this procedure for all frames establishing points a102 through a106.

Measure the girths for each frame from the "a" point to the upper GU, and lower seams, GL

The shape of the developed shelI plate is determined as follows and shown in Figure 1.4.4.2

1. Draw a vertical line representing frame 100.
2. Mark a point on it representing a100.
3. Set of GU1OO and GL1OO.
4. Draw a line through a100 normal to the vertical line extending beyond anticipated frame 101 line.
5. Draw a line parallel to the normal line a distance of bl0l - al0l to the appropriate side of the normal line.
6. Draw lines parallel to the parallel line established in 5) at distances above and below the line equal to GU101 and GL101 respectively.
7. Draw an arc of radius A' horn upper seam point on frame 100 and the same for the lower seam point with radius equal to G'. The upper and lower seam / frame 101 intersection points are where the arcs intersect the lines drawn in 6).



CENTER SQUARING OFF METHOD

FIGURE 1.4.4.1 - SHELL PLATE BODY PLAN

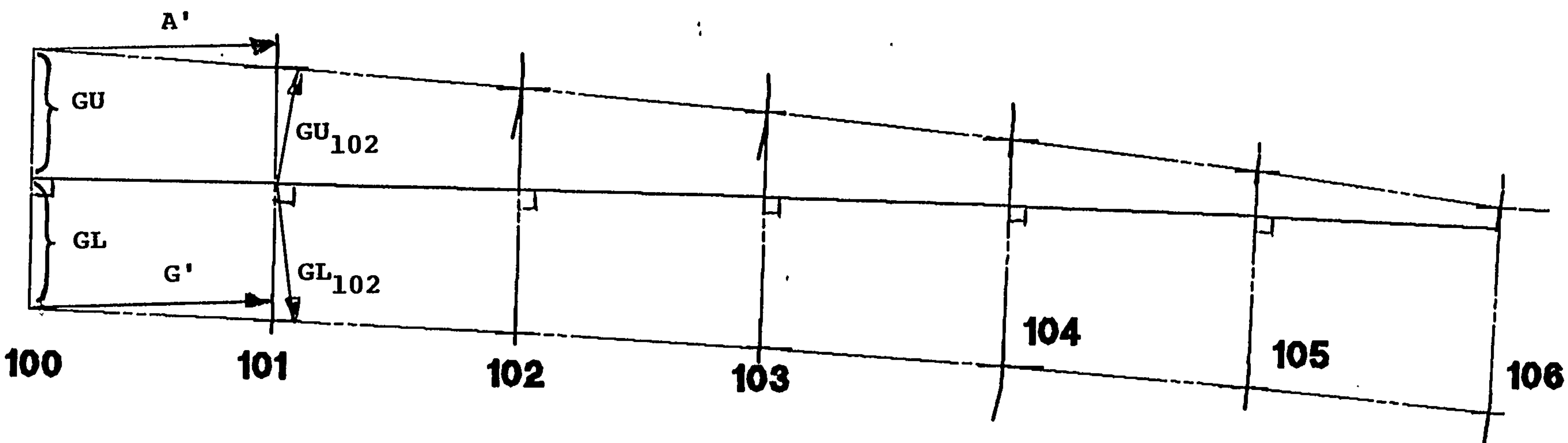


FIGURE 1.4.4.2 - CENTER SQUARING OFF METHOD SHELL PLATE EXPANSION

8. Draw a straight line between the upper and lower seam / frame 101 intersection points.
9. Where the line drawn in 8) intersects the line drawn in 5), designate the point al0l
10. Repeat steps 4) through 9) for frames 101 through 105 using appropriate expanded seam distances for the upper and lower seams, upper and lower girth lengths and derived “a” points.
11. Draw curves through the upper and lower seam points.

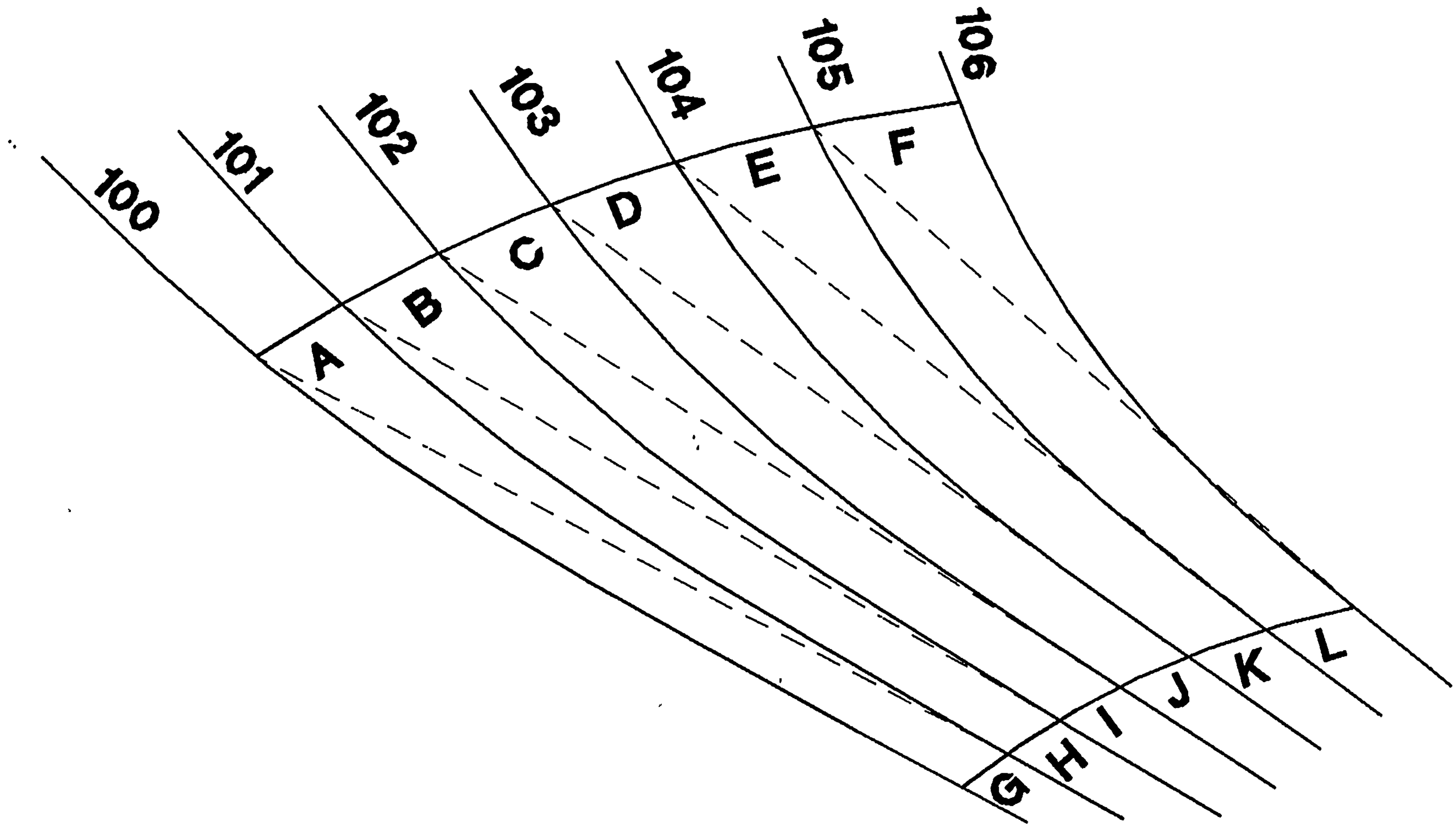
1.4.5 Single (Edge) Triangulation Method

The triangulation method is based on the concept that any surface can be accurately developed into a flat pattern made up of expanded triangles.

Figure 1.4.5.1 shows the shell plate on the body plan. Single diagonal lines are drawn on the body plan from opposite comers of each plate panel between frames. The diagonals are expanded on the standard frame grid, as shown in Figure 1.4.5.2. Again, the upper and lower seams are expanded.

The shape of the developed plate is determined as follows and shown inFigure 1.4.5.3

1. Draw a vertical line and set off the girth length G100
2. Draw an arc of radius A’ from the upper seam point for frame 100
3. Draw an arc of radius a’ from the lower seam point for frame 100
4. The intersection of the arcs drawn in 2) & 3) is the upper seam point for frame 101
5. Draw an arc of radius G’ from the lower seam point for frame 100
6. Draw an arc of radius G101 from the upper seam point for frame 101
7. The intersection of the arcs drawn in 5) and 6) is the lower seam point for frame 101
8. Repeat steps 2) through 7) to determine all upper and lower seam / frame intersection points
9. Draw curves through upper and lower seam points



SINGLE (EDGE) TRIANGULATION METHOD

FIGURE 1.4.5.1 - SHELL PLATE BODY PLAN

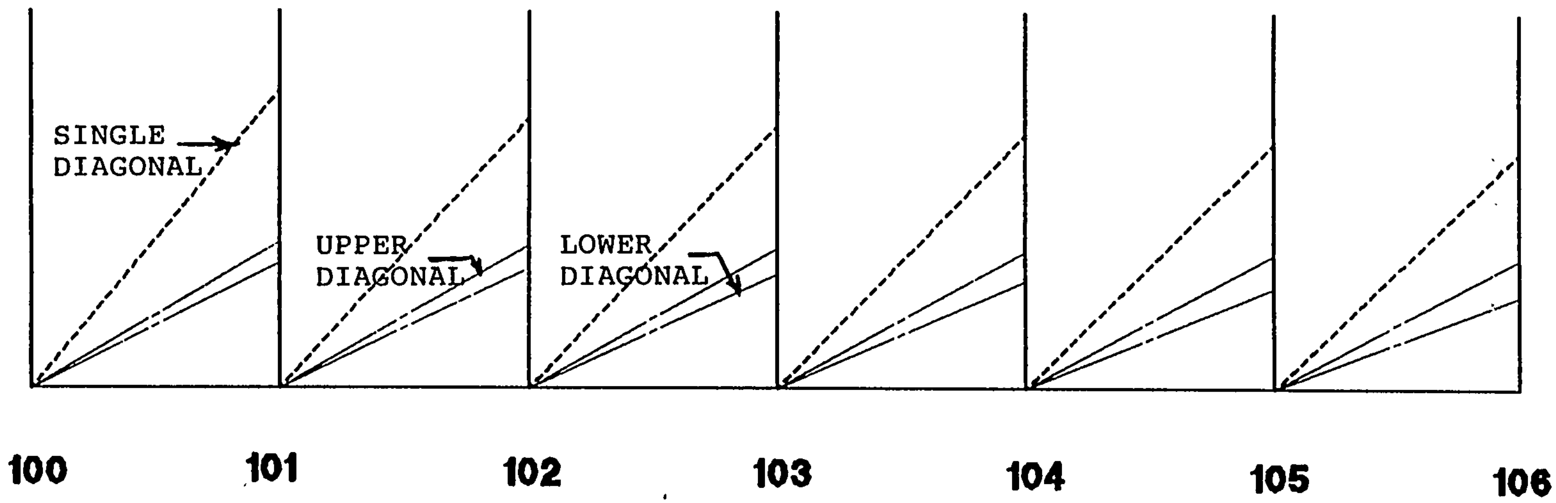


FIGURE 1.4.5.2 - EXPANSION OF TRIANGULATION DIAGONALS

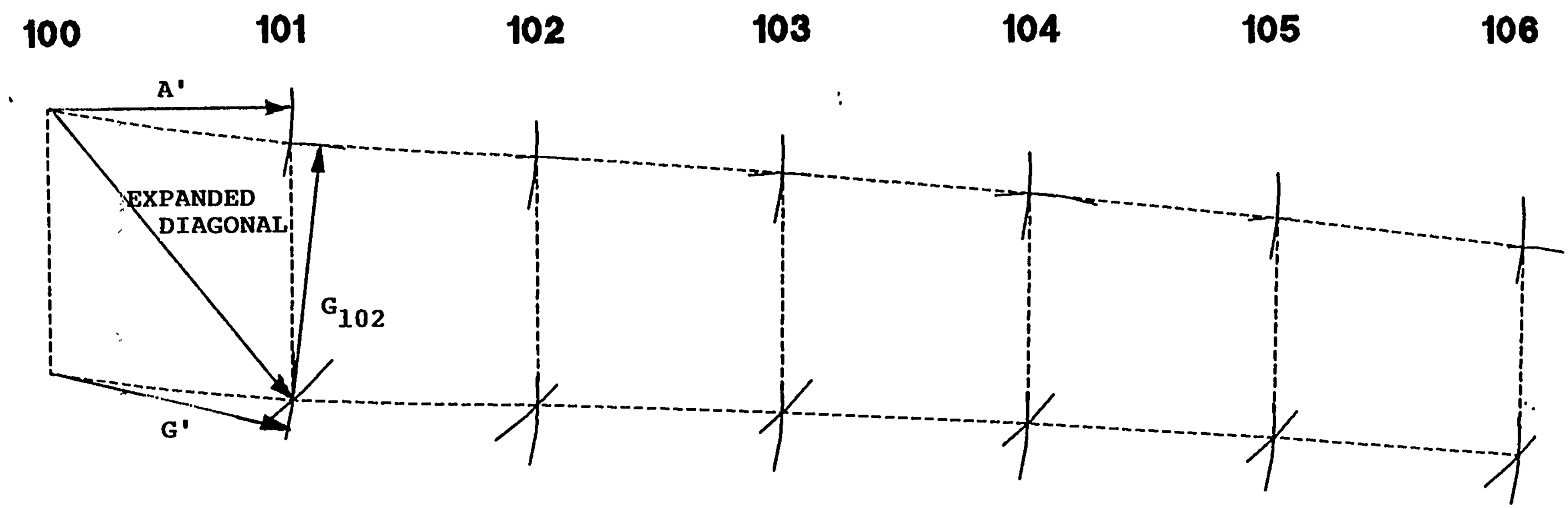


FIGURE 1.4.5.3 - SINGLE TRIANGULATION METHOD SHELL PLATE EXPANSION

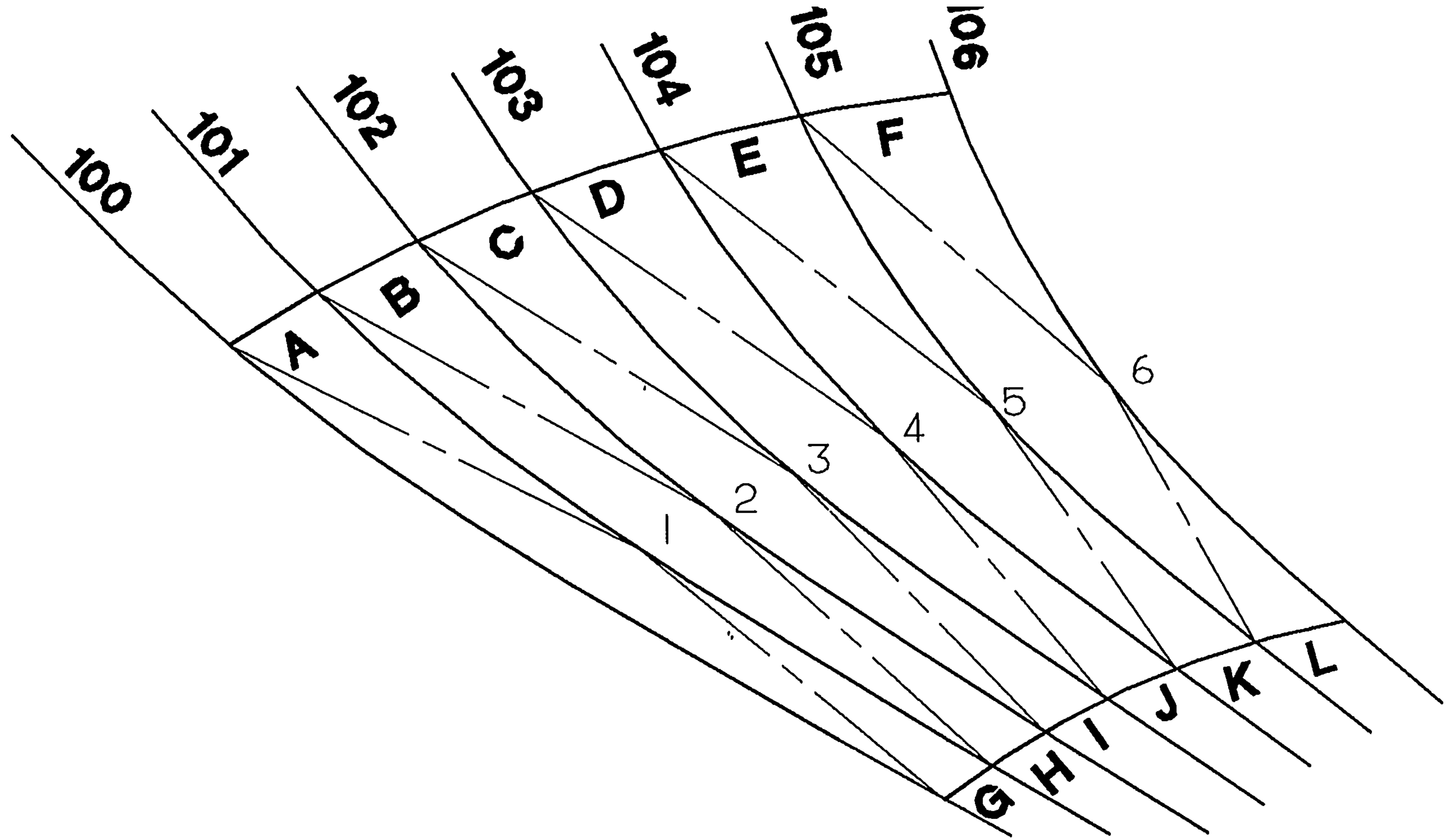
1.4.6 Double (Center) Triangulation Method

Triangulation can be single, as described in 1.4.5, or multiple. Manual triangulation methods usually do not use more than double triangulation. However, multiple triangulation (3 or 4) is sometimes manually used for extremely curved shelI PIates.

Figure 1.4.6.1 again shows the shell plate on the body plan. On frames 102 through 106 the mid points of the girth lengths are determined and designated points 1 through 6, Diagonals are drawn from upper and Iower seam points to the mid points on adjacent frames. Again the upper and lower seams are expanded. The upper and lower diagonals are expanded in the same way as the diagonals in 1.4.5, as shown in Figure 1.4.5.2 on a standard frame space grid.

The shape of the developed plate is determined as follows and shown in Figure 1.4.6.2.

1. Draw a vertical line equal to the girth length G100
2. Draw an arc of radius au100 from the upper seam point on frame 100
3. Draw an arc of radius a(100 from the lower seam point on frame 100
4. Where the arcs drawn in 2) and 3) intersect is the developed position of point 1 designated 1’
5. Draw arcs of radius half G101 with center 1’ above and below the point
6. Drawan arc of radius A’ from the upper seam point on frame 100
7. Where the arcs drawn in 5) and 8) intersect is the upper seam point for frame 101
8. Draw an arc of radius G’ from the lower seam point on frame 100
9. Where the arcs drawn in 5) and 8) intersect is the lower seam point for frame 101
10. Repeat steps 2) through 9) with the appropriate expanded diagonals and seam distances to derive all upper and lower seam/frame intersection points
11. Draw curves through upper and lower seam points



DOUBLE TRIANGULATION METHOD

FIGURE 1.4.6.1 - SHELL PLATE BODY PLAN

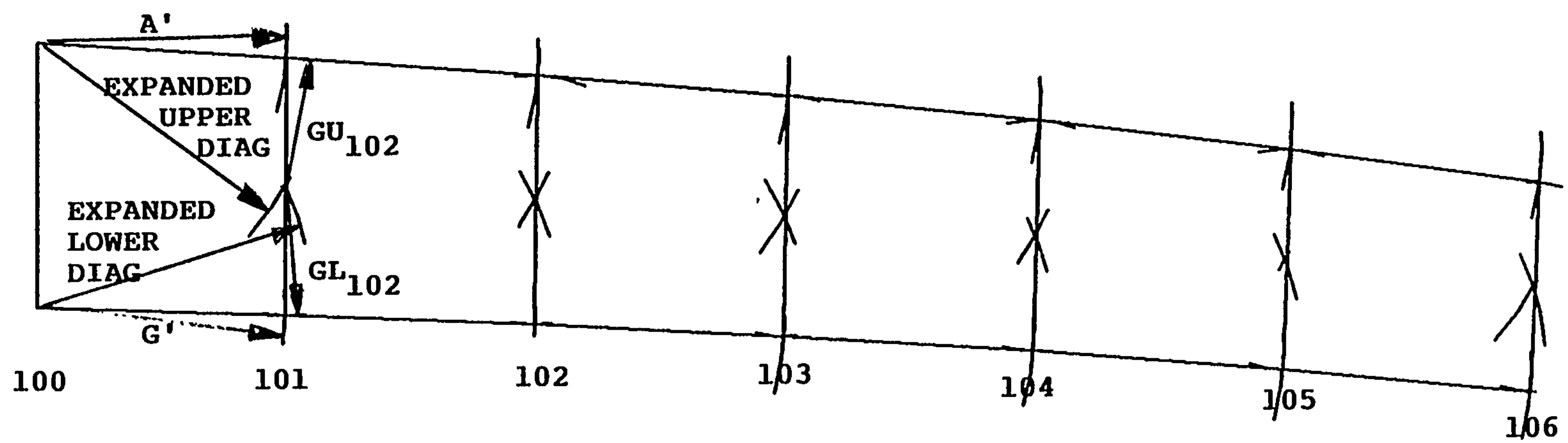


FIGURE 1.4.6.2 - DOUBLE TRIANGULATION METHOD SHELL PLATE EXPANSION

1.4.7 Geodetic Line Method

The Geodetic Line method is very similar to the Girth Length method except it uses an improvement over the straight line datum, namely the geodetic line.

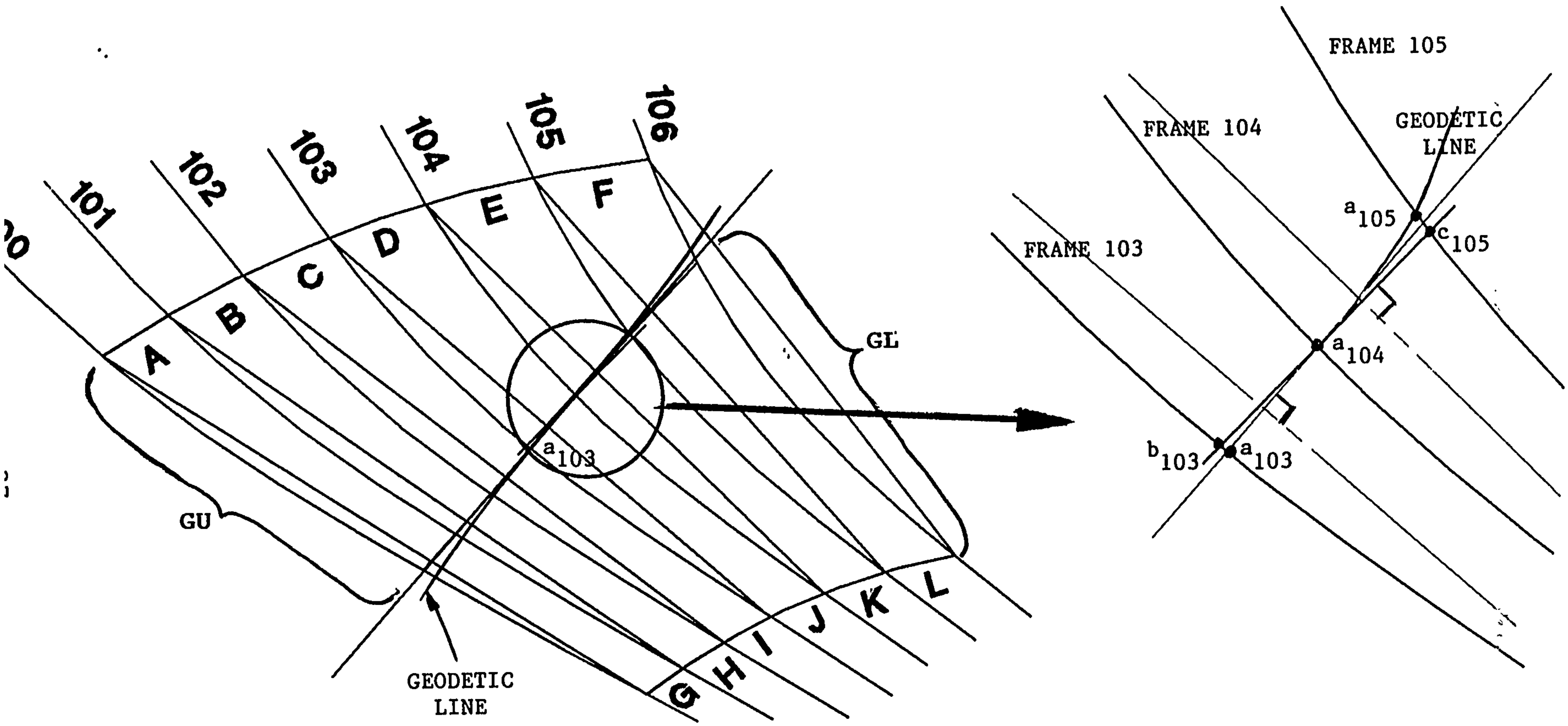
A "geodetic line" on any developable surface will be straight when developed. For surfaces representing the hull of a ship it has been found that, within certain Iimits, the geodetic line approach is a reasonable assumption. The geodetic line is developed on the body plan as shown in Figure 1.4.7.1 and as described below

1. Draw chord lines between upper and lower seams for each frame.
2. Select the girth mid point on a middle frame such as a103 on frame 103.
3. Draw a line through al03 normal to the chord Iine for frame 103.
4. Designate the intersection of this line and the frames 102 and 104, al02 and al04 respectively.
5. Draw a line through al04 perpendicular to the frame 104 chord line.
6. Designate where line drawn in 5) intersects frames 103 and 105, b103 and b105 respectively.
7. Determine point al05 on frame 105 so that distance b103 - al03 is equal to b105 - a105.
8. Repeat steps 5) through 7) for a102 and each "a" point for frames 100, 101,105 and 106.
9. Draw a curve though points a100 through a106. This is the approximate geodetic line for the shell plate.

Upper and lower seams and the geodetic line are expanded and the girths above and below the geodetic line for each frame are Iifted from the body plan.

The shape of the developed plate is determined as follows and shown in Figure 1.4.7.2:

1. Draw a straight horizontal line.
2. Set the mid point a103
3. Set of points for expanded geodetic line on frames 100 through 106.
4. Draw a line through point a103 normal to the horizontal line.
5. Draw an arc of radius C' from the upper seam point on frame 103 toward frame 102.
6. Draw an arc of radius GU102 from point a102.
7. The intersection of the arcs drawn in 5) and 6) is the upper seam point on frame 102.
8. Repeat steps 5) through 7) to determine all upper and lower seam/frame intersection points.
9. Draw curves through upper and lower seam points.



GEODETIC LINE METHOD

FIGURE 1.4.7.1 - SHELL PLATE BODY PLAN

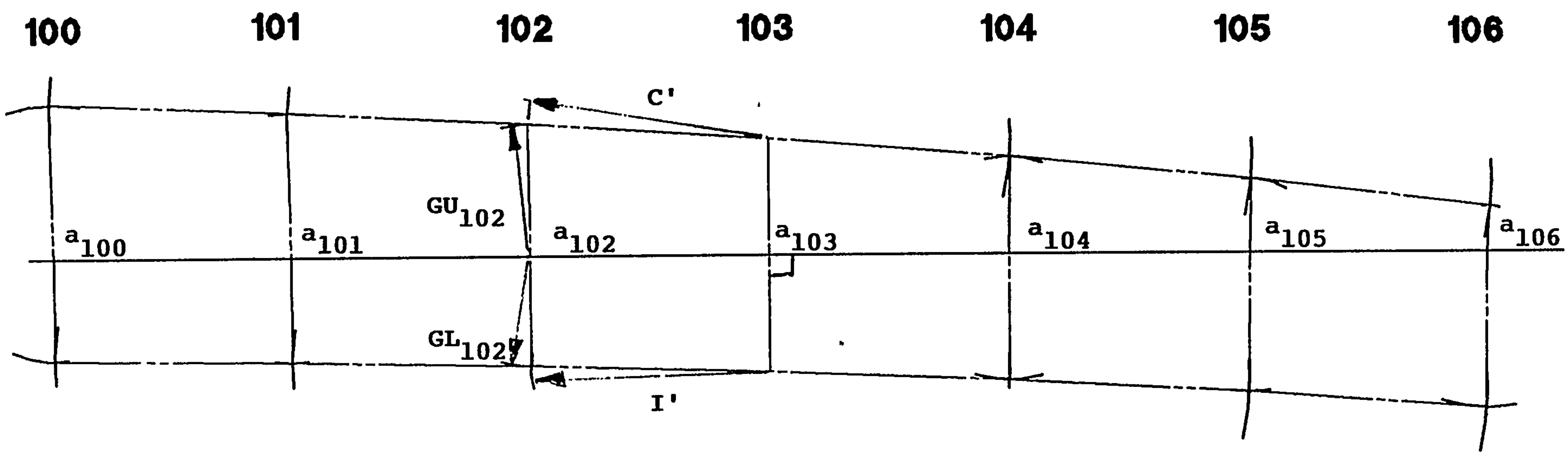


FIGURE 1.4.7.2 - GEODETIC LINE METHOD SHELL PLATE EXPANSION

1.4.8 Comparison of Traditional Manual Methods

Figure 1.4.8.1 shows an overlay of all the flat patterns developed by the described traditional manual methods. Figure 1.4.8.2 give an enlargement of the right side of the plates to show differences better.

It can be seen that there are significant differences between the various developed shapes. There is general agreement for five out of the seven methods. Even so it is of concern that there are differences as the plate was not a “difficult” plate and the seams were reasonably straked. That is they were selected to easily wrap the hull surface rather than buttocks or waterlines as many modem plates are arranged to suit modular construction.

The method with the major difference is the Edge Squaring Off using the upper seam. It is “off” by over 10 inches at the upper right hand comer compared to the Double Triangulation Method.

The other methods are off by up to 2.5 inches from the Double Triangulation Method.

The Single Triangulation Method is off because of a strange hook resulting from the curvature change between frames 100 and 101.

It is generally acknowledged that multiple triangulation will give the best approximation for a flat pattern development of a surface with compound curvature. Based on this, it would appear that the order of acceptability of the different manual shell development methods is

Double Triangulation
Center Squaring Off
Geodetic Line
Edge Squaring Off using Lower Seam
Girth
Single Triangulation

The Edge Squaring Off using the Upper Seam does not appear to be an acceptable approach.

KEY GM - GIRTH METHOD
ESMUS - EDGE SQUARING METHOD UPPER SEAM
ESMLS - EDGE SQUARING METHOD LOWER SEAM
CSM - CENTER SQUARING METHOD
STM - SINGLE TRIANGULATION METHOD
DTM - DOUBLE TRIANGULATION METHOD
GLM - GEODETIC LINE METHOD

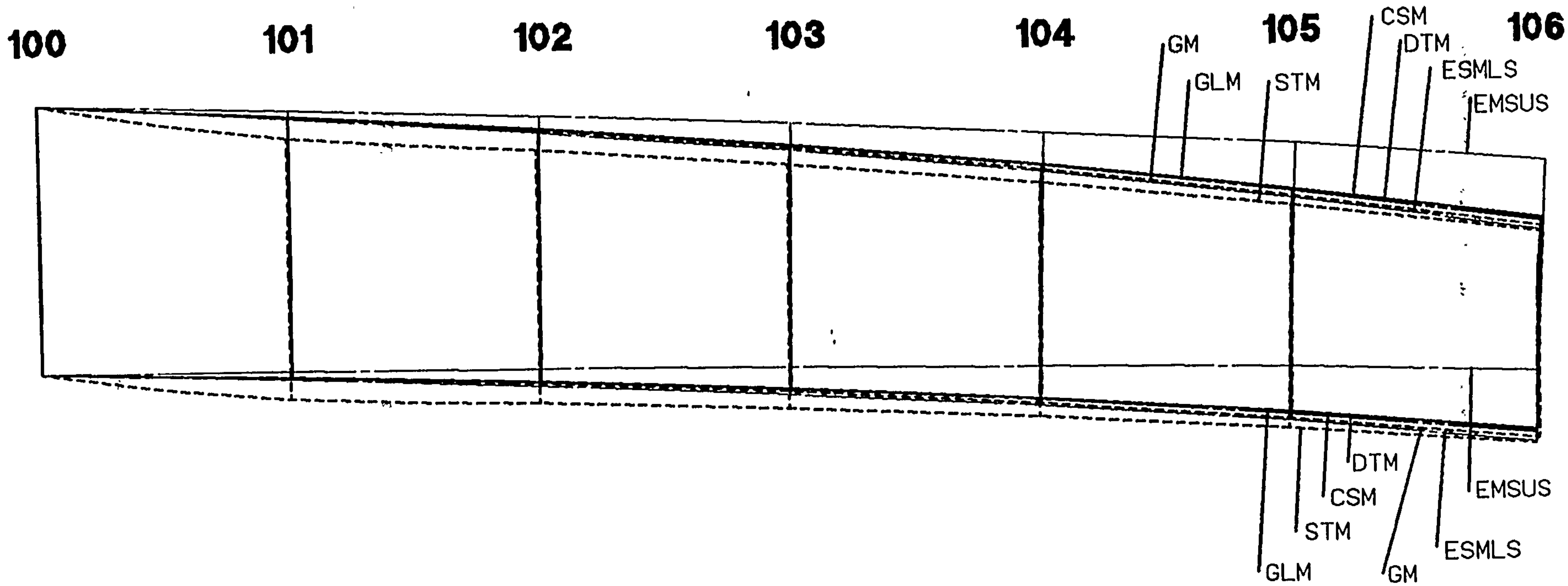


FIGURE 1.4.8.1 - OVERLAY OF ALL MANUALLY DEVELOPED SHELL PLATES

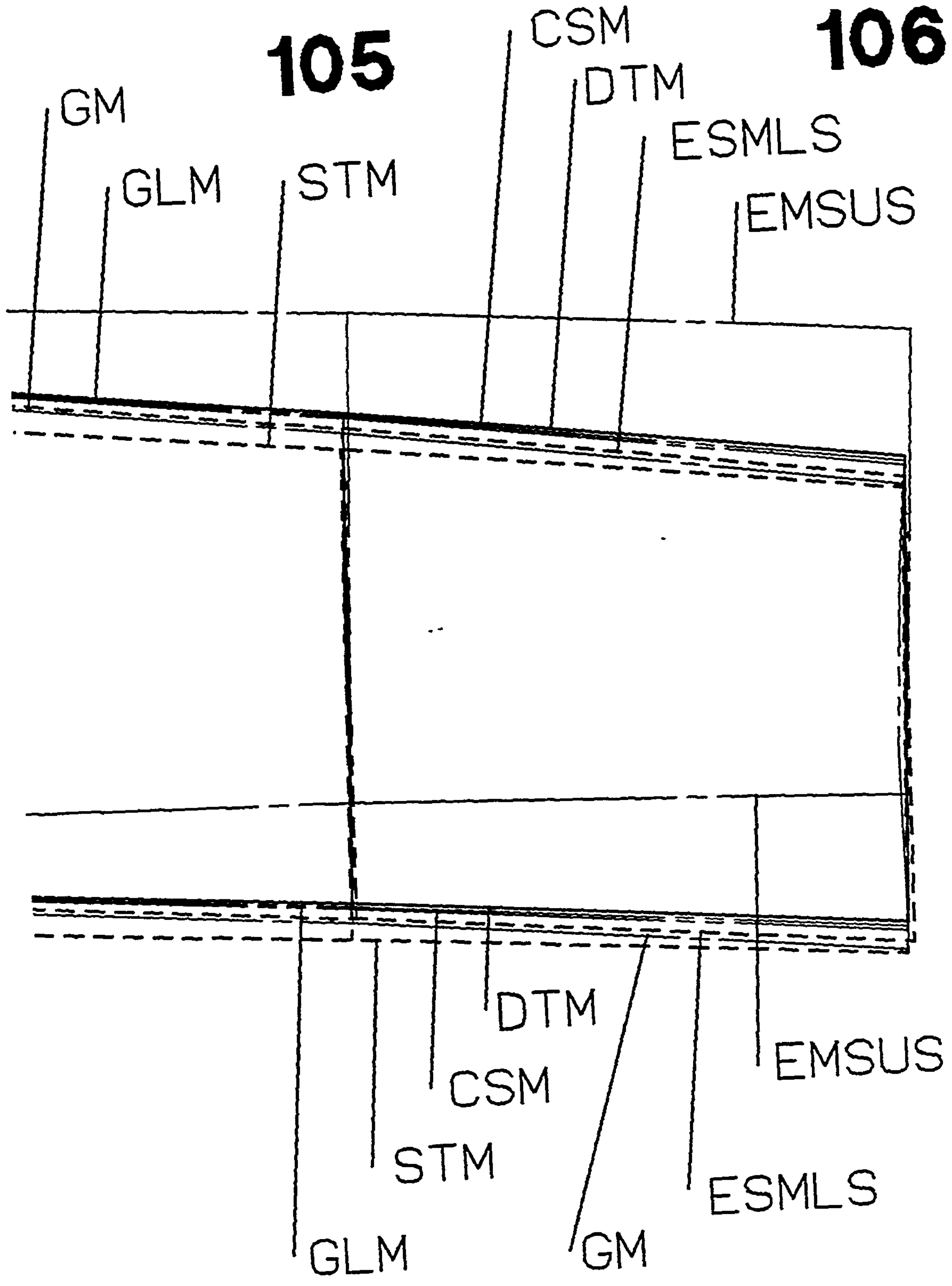


FIGURE 1.4.8.2 - ENLARGEMENT OF PLATE END TO SHOW DIFFERENCES

2..0 SHELL PLATE DEVELOPMENT PROBLEMS

2.1 General

If there were no problems with the current development of curved shell plates, this study would not have been undertaken and this report would not have been prepared. In performing the study it was determined that the problems are viewed differently by shipbuilders and the CAL developers. This is surprising when it is remembered that computer aided lofting shell development methods have been in use for over twenty years. It would seem reasonable to expect developers and users (shipbuilders) to have worked out the problems or at least agreed what they are. However, as will be seen from the following discussion, this does not appear to be the case.

Before discussing the problems, it is necessary to define some of the terms that will be used.

CURVATURE is smooth deviation from a straight line. As applied to a surface it is smooth deviation from a flat plane.
SINGLE CURVATURE is deviation in only one direction.
DOUBLE CURVATURE is deviation in two directions approximately normal to each other.
REVERSE DOUBLE CURVATURE occurs when curvature in the two directions is in opposite directions.
STOCK is excess material added to the developed flat plate shape. It is usually a fixed allowance such as one inch offSet from the developed shape of the seam/s and butt/s.

Figure 2.1.1 gives examples of plates with the above types of curvature. Shell plates in the parallel mid body at the bilge would be single curvature plates. Most other curved shell plates would be double curvature. Shell plates at the stem and stem can be reverse double curvature type especially in “fine” hull forms.

Modular construction divides a ship’s hull into structural blocks. Figure 2.1.2 shows the aft portion of the block definition drawing for a typical single screw ship. Figure 2.1.3 shows the block above the propeller aperture upside down as it would probably be built It contains shell plates with significant reverse double curvature as shown. It also shows the four erection seams, two transverse erection butts and the transom erection butt The upper seams and the transom butt are in the same plane, a water line. The block contains a total of 15 shell plates.

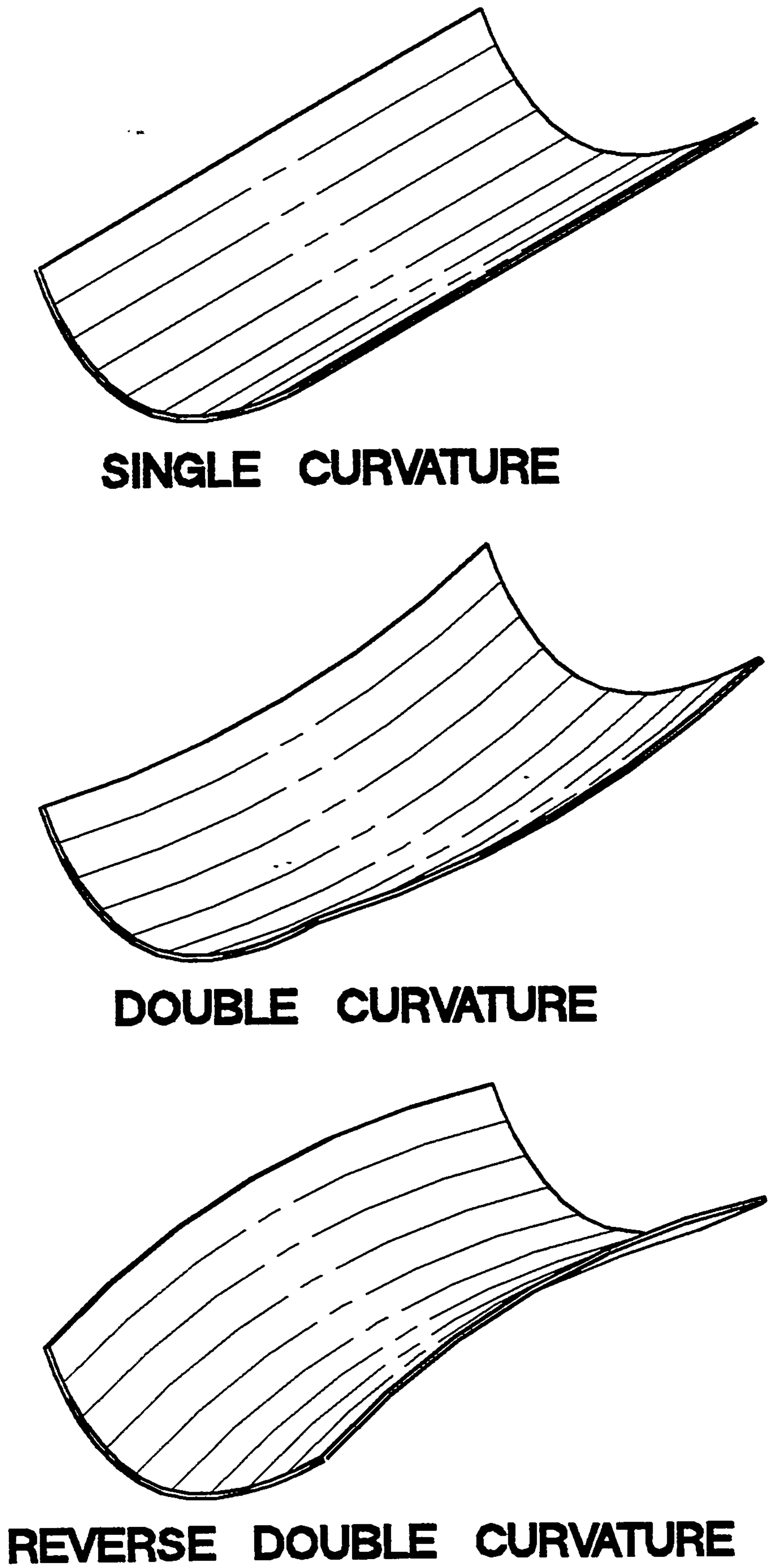


FIGURE 2.1.1 - CURVATURE DEFINITIONS

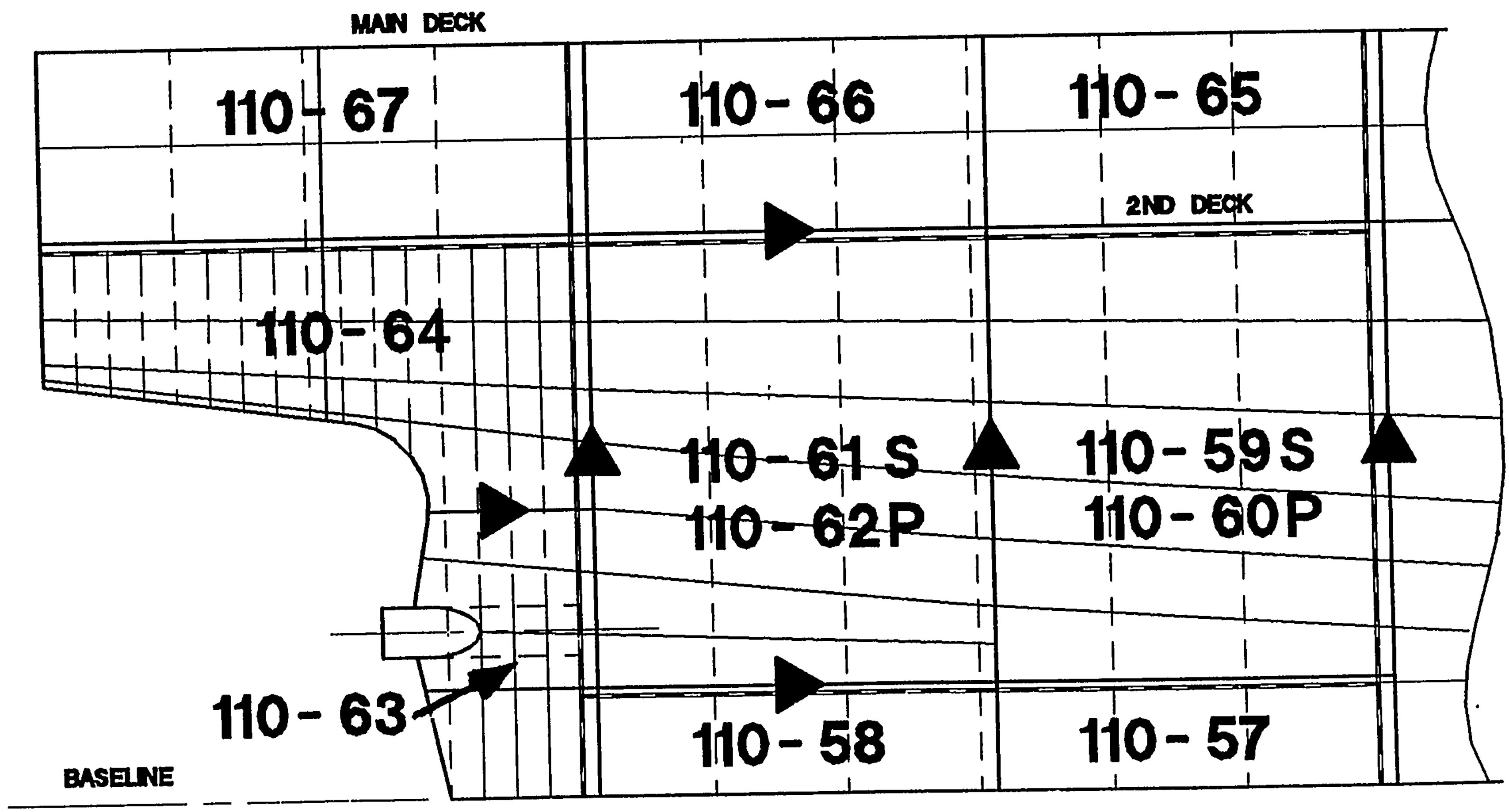


FIGURE 2.1.2 -BLOCK DEFINITION DRAWING

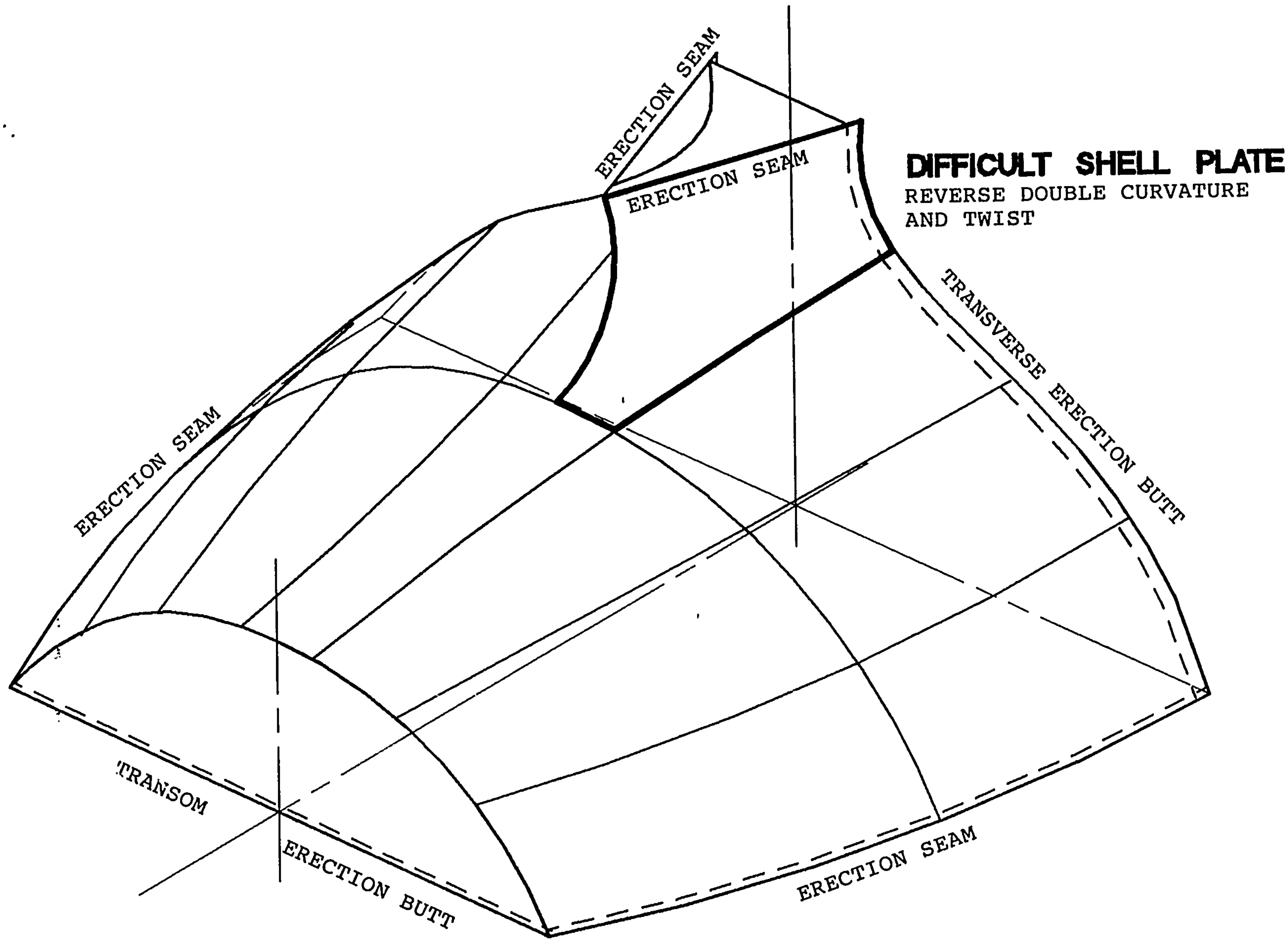


FIGURE 2.1.3 - ISOMETRIC VIEW OF BLOCK 110-64

2.2 U.S. Shipbuilding Situation

Most shipbuilders in the U.S. are not satisfied with the current shell development situation. They want to be able to cut shell plates neat That is without excess material to be "cut in" during fitting the plates on the assembly plattens or structural blocks on the building berth. They view their inability to do this as a limitation of current computer aided lofting systems shell development technology.

While a large number of a ship's shell plates will be flat in the "flat of side" and "flat of bottom", and developable at the bilge radius in way of the parallel body, there are still many that have complex curvature. It should be obvious to most people involved in the design of ships that normal ship hull shapes do not have developable surfaces in the area of curved plates.

AU.S. shipyard provided the following information for a typical high speed container ship, which gives an appreciation of the problem. Atypical ship has 35,000 parts that are lofted. 45% or about 16,000 are N/C cut parts. The number of shell plates on such a ship would be about 800. The shipyard would not use their CAL shell development program for about 80 shell plates located in the bow and stem. They would use their experience to locate, slrake and size these plates and manually develop them. Of this 80, half would require forming over a built up "form, set or bed". This same shipyard reported particular problems with shell plates that contained both flat and compound curvature, such as plates crossing the flat of bottom or side tangency lines.

Table 2.2.1 is similar data for a tanker taken from the Avondale/IHI Technology Transfer data (2). From this it can be seen that only a small percentage (15.1%) could be formed by just rolling. The majority of the plates required rolling and then further forming by line heating. This is probably due to decision not to use packed rolls for plates with back set, but rather to simply roll them first and use line heating to obtain longitudinal curvature.

It should also be noted that a smaller number of actual plates were curved, 296 versus 800. This is because the first vessel had more shape throughout its length or less parallel body than the second ship.

Accuracy Control has contributed to the better fit up of internal structure in subassemblies and structural blocks but because of the uniqueness of individual curved shell plates, the forming techniques and shape control used, it is difficult to apply to shell plates and thus it is not possible to benefit from the accuracy control process. A recent report(3) from a Japanese shipbuilder for additional marking on shell plates suggests one way that it could be applied to the fit up of shell plate to shell plate This is shown in Figure 2.2.1. The method consists of providing a continuous marking inside the seams and butts at a constant distance for every shell plate. After a shell pIate is joined to another

TABLE 2.2.1

ESTIMATION OF CURVED SHELL PLATES ON EXXON

1. Amount of curved shell plates (per one ship)

Aft Construction Part	35 Plates*
Engine Room Part	84 Plates
Cargo Hold Part	112 Plates
Fwd. Construction Part	67 Plates*
TOTAL	298 Plates

NOTE * ESTIMATED FROM DRAWINGS

2. Classification of curved plates bending works

BENDING PROCESS	QUANTITY OF PLATES	PERCENTAGE
a) No roll	26	8.7
b) Roller (or press) only	45	15.1
c) Roller and Line Heating	196	65.8
d) Line Heating Only	20	6.7
e) Roller and Forming jig	11	3.7
TOTAL	296	100.0

Roller work= b + c + e = 45 + 196 + 11 = 252 plates / one ship

Line Heating work= c+ d = 196 + 20 = 216 plates / one ship

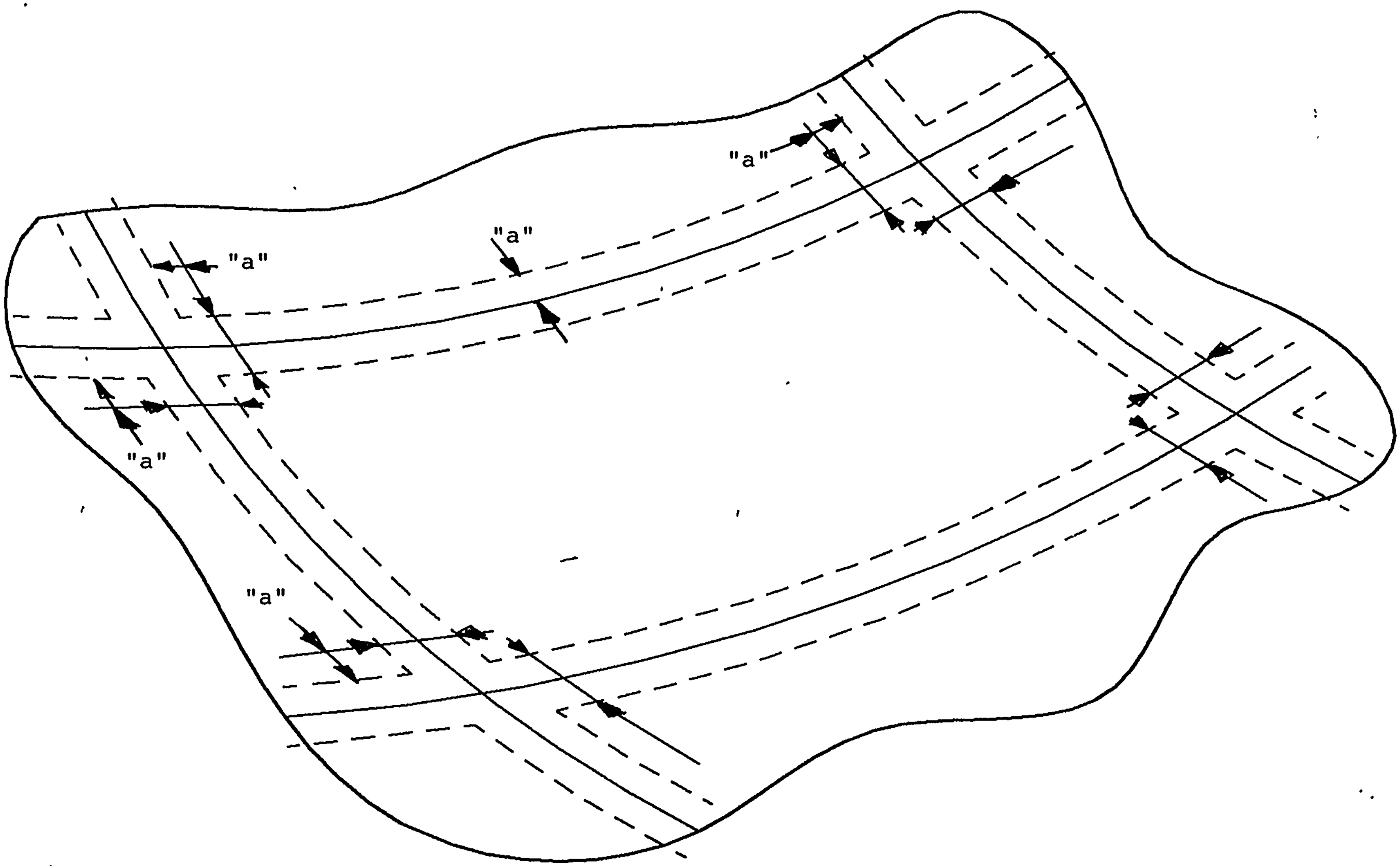


FIGURE 2.2.1 - USE OF STANDARD SHELL PLATE MARKING FOR ACCURACY CONTROL OF FIT UP TO ADJACENT SHELL PLATES

and after the internal structure is completely welded to the shell plates, measurements can be taken from one line to its adjacent plate line and the distance recorded. This would be applied to all the usual accuracy control analysis tools and the results used to control the shell shaping/fiting process and to show when improvements were necessary. It would also provide the necessary raw data from which to develop weld shrinkage data

It is possible to utilize developable surfaces on smaller hard chine or multi-surface combination hulls. However, large ships are generally not deliberately designed with developable surfaces.

Shipbuilders report that they have problems with individual shell plates fitting pin jigs or egg-crated support structure. Some report apparent plate shape acceptability but plate marking out of alignment with internal structure. This has led them not to mark such plates by N/C, but using the IHI "Key Line" method to layout the marking AFTER the plates are formed, set on jigs and joined together. The IHI Key Line method was described in detail in the Avondale/IHI Shipbuilding Technology Transfer reports (2), and is reproduced in Appendix 9.3 for convenience of readers. Some shipyards use the Key I.ine method to CHECK the N/C marking after the plates have been joined to form a panel.

It is possible to use part of the Key Line approach as accuracy control input for shell panels once they are joined. This would be accomplished by recording out of shape as measured-by differences between the "thread lines" on the back set and key line templates and the corresponding actual thread lines.

Others shipbuilders problems with the "squareness" of structural block shell plates, reporting comers being up to 3 inches out of true location on a typical block with curved shell plate.

Some shipbuilders report that a major cause of these problems is inadequate definition of the ship's lines, especially in areas of extreme compound curvature. This suggests that better definition through closer spacing of control lines (frames, waterlines and buttocks) and better checking for fairness in these regions is necessary and should be an essential part of the process of lines fairing. It is too late to discover bumps, hollows or knuckles in the hull surface during shell plate development Because of this underdefined lines problem, some shipbuilders use full scale mock ups to ensure smooth surfaces. Typical areas where this is done are

- Segmented or "orange peel" plates such as spherical bulbous bow plates

- Plates with extreme twist

This inability to consistently process shell plate with acceptable shipbuilding accuracy forces the shipbuilders to “play safe” and use “stock” on at least one butt and one seam for each curved shell plate structural block. Then either cutting the stock material off as the blocks are aligned or before erection through the use of one of the current accurate measurement and alignment methods. Either way requires considerable skill and significant effort (man hours) and time (longer build duration) to accomplish the fit up, removal of the stock and prepare the edge for welding.

Areas of a ship’s hull, identified by shipbuilders, that can cause problems are

- Clipper Bows - Soft Nose Stem
- Cruiser Stems
- Single Screw Apertures - Stem Frames
- Forebody and Aft body shoulders
- Blocks in the fore and aft bodies with vertical butts and horizontal seams
- Bulbous Bows
- Sonar Domes
- Heavy Flare in “fine” hulls

Some shipbuilders/designers avoid some of these problems by utilizing large castings especially for stems and stem frames.

2.3 Computer Aided Lofting Developers’ Experience

The participating CAL developers’ reports are reproduced in Appendix 9.1. The following is a summary of the reported known shell plate problems and how the different systems take care of them.

All the participating CAL developers are aware of shell plate problems but they do not see them as a limitation of the methods they use.

They all point out that shell development of double curvature shell plates is an approximation. There is no exact “unwrapped” flat shape for such curved plates. However, they believe that the approximation gives developed flat shapes for plates that are well within current shipbuilding tolerances.

A number of them stress that all shell plate development requires system skilled and lofting experienced users with knowledge of their shipyard’s forming and fabrication capabilities and limitations.

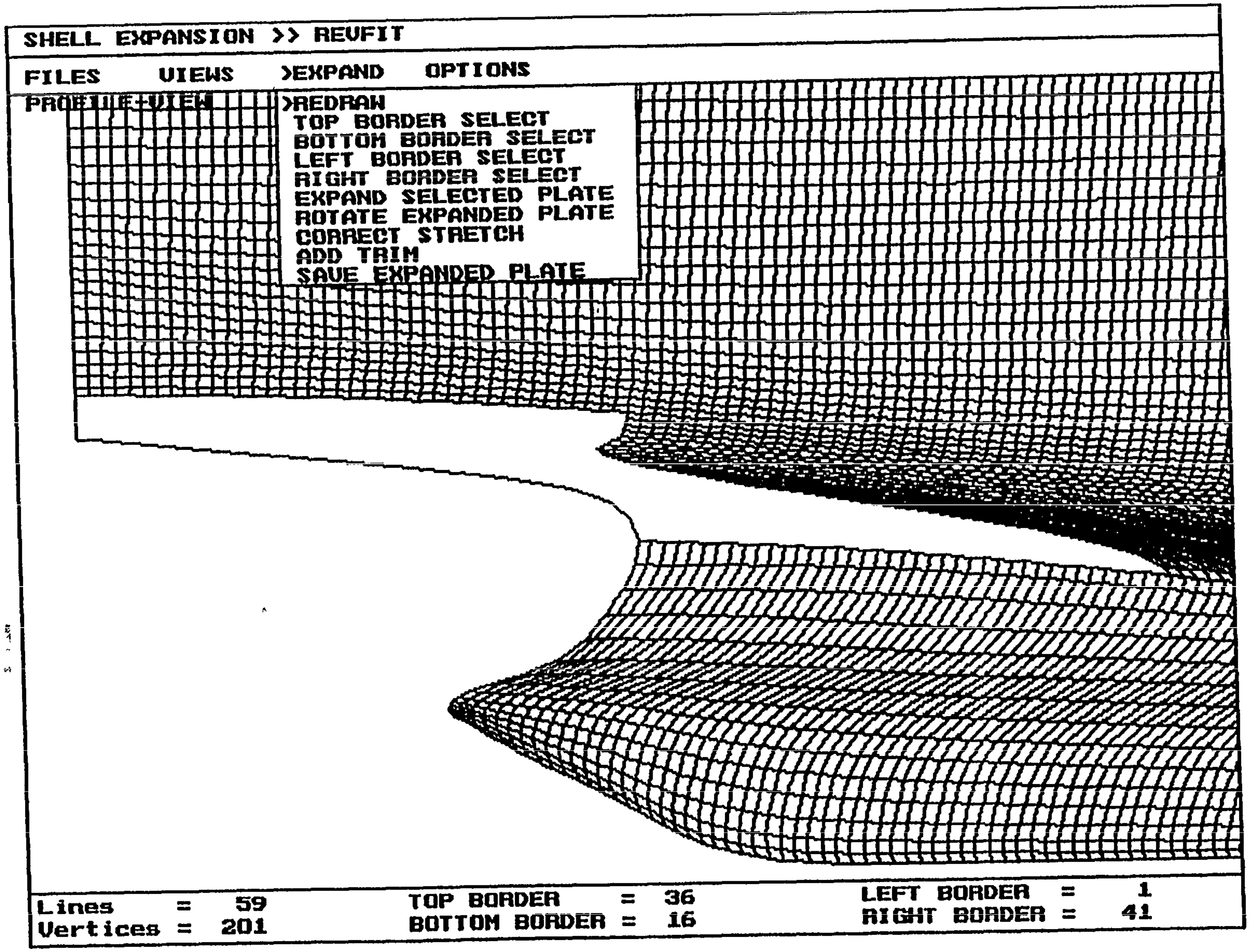
Albacore Research recognizes that some extreme double curvature shell plates cannot be adequately expanded into a flat shape. They base the decision of which plates cannot be developed on a review of the fore and aft deflection of the transverse mesh lines as shown in the Shell Expansion View produced by their system. Actually, the areas on the hull that cannot be developed show as clear areas, without the mesh. Figure 2.3.1 is reproduced from Appendix 9.1.1, Figure 9 and illustrates this attribute.

BMT also recognize the spectic areas of certain ship hulls that require special attention and the use of experienced Ioftsmen. These Ioftsmen should not only be experienced in the application of the CAL system but also with their shipyard's shell forming constraints. The BMT system also has an attribute wherein the direction and magnitude of the curvature are displayed by tufts of principal curvature for the hull surface patches.

Cali points out that "development of a compound curved surface into a flat pattern is a mathematical impossibility." Based on this the problems are essentially related to the acceptance of the approximation and lack of allowance by the shipbuilders to account for the inexactness of the approximation for specific shell plates. The accuracy of the approximation is significantly influenced by the selection of the seams and butts. The effect of straking to suit modular construction can create problems by twisting the shell plates. These problems are addressed by considering the correct "priorities" in defining the shell seams and butts. These priorities incorrect order should be

- Hull Form Complexity
- Straking - Selection of butts at curvature inflexion points
  - Selection of block seams to suit hull shape
- Material Utilization

Coastdesign addresses problems with using small craft developable surfaces if the designer's lines must be maintained. They point out that only the deck edge and the chines should be defined, as the frame sections will be derived from the developable surfaces in the AutoPlex system. Also for small craft the shell plate thickness is small and the AutoPlex system ignores it It is possible to overcome this problem when using thick shell plates in AutoPlex by contracting or expanding the hull lines. The forming of compound curvature plates is basically accomplished by applying strain to the flat plate to deform it into the designed shape. Theoretically, the development of such a plate could be exact by using a finite element method. However, there is no practical method of applying *e strain to the plate exactly as required. Also the resulting deformation would increase and decrease the plate thickness as the plate material was stretched or compressed. By using a finite element approach, strain maps are produced by the system. They can be used in the forming process by showing where most of the strain and thus the application of the deforming force should be applied.



Stern of vessel with extreme fore/aft deflections in transverse lines

FIGURE 2.3.1

Kockums Computer System report that most of the known shell plate problems can-be resolved by correct-orientation of individual plates to the expansion curves and use of smaller plates where curvature is large. The AUTOKON system's interactive capability makes it relatively easy to try different approaches for the development of difficult shell plates such as smaller plates, transverse expansion curves as an alternative to longitudinal expansion curves and closer spacing of the expansion curves.

Senermar points out that one of the main problems with shell plate development and forming is the verification of the plate shaping and discusses two ways that this can be done. Of interest is their use of a longitudinal template with transverse roll sets as a means for better control. Senermar also compensates for weld shrinkage, and their system can take care of it in two ways. First, they can compensate for weld shrinkage in both the transverse and longitudinal directions by the same or different shrinkage factorsas prefered and selected by the user, and all coordinates of the deveIoped shell plate are automatically adjusted. Second, instead of shrinkage factors, a constant allowance can be added to any of the plate edges.

2.4 Foreign Shipbuilding Situation

An attempt was made to obtain the viewsof foreign shipyards on this matter by contacting four foreign shipbuilders. Unfortunately, they all chose not to participate. As an alternative, papers presented by foreign shipbuilders on the subject (4,5 and 6) were reviewed to obtain some idea of their thinking / problems. From this review, and personal discussions between the team and foreign shipbuilders, it can be stated that they do not see the shell development problem as much of a problem as some of the U.S. shipyards see it

Their message is that successful shell plate forming and erection is as much or more dependent on the material handling and forming equipment and the skills and training of the forming and erection workers, as it is on the computer aided Iofting method capability.

3.0 AIRCRAFT INDUSTRY PLATE DEVELOPMENT PROBLEMS

3.1 General

The aircraft industry has some problems that are similar to shipbuilding and others that are unique. As already reported, early aircraft lofting used shipbuilding lofting techniques and Ioftsmen. Most existing aircraft manufacturers have their own computer aided lofting system. They have special attributes to handle their unique needs.

The simple shaped plates in the fuselage, wings and tail present no problems. It is the leading edges of the wings and tail, forward and aft ends of the fuselage and engine nacelle leading edge.

The problems are handled by different approaches depending on need as follows

- Sheet stretching or hammer forming over dies
- Sheet shot peening
- Composite molds

Where plate development is performed it is done by multiple triangulation and stock is provided for fit up.

4.0 DESCRIPTION OF CAL SHELL PLATE DEVELOPMENT METHODS

4.1 General

The six participating CAL developers' reports, in which they describe their shell development methods, are reproduced in Appendix 9.1. A brief discussion of their methods is first given for each system and then a summary of them all is presented.

The discussion will emphasize both similarities and differences of the systems and highlight any unique and production oriented (shipyard useful) attributes. For a full understanding of the different systems, the reader is referred to the appendices.

It should be obvious that a successful shell development system must be part of a total system that has a successful fairing system. It should be equally obvious that experienced loftsmen / users are required to develop successful lines. This study assumes that this condition exists for the participating CAL developers. Further, that the CAL fairings must produce fair and smooth hull surfaces with no bumps or hollows.

4.2 Albacore Research Ltd

Albacore Research Ltd. is a relatively new PC based system. It developed from research work carried out at the University of British Columbia Albacore Research Ltd. has its office in Victoria, B.C.

The Albacore Research Ltd. system is called ShipCAM3. ShipCAM3 is an integrated shipbuilder's software package which includes tools for computerized fairing lofting, developable surface expansion and shell expansion. It has been specifically developed for the small and medium sized shipyards, but also large shipyards may find it useful. It runs on IBM PC compatible computers. ShipCAM3 closely integrates with off-the-shelf CAD programs, such as AutoCAD. ShipCAM3 passes the geometric data such as faired lines, frames and developed shell plating to CAD systems for detailing.

ShipCAM3 has been marketed for two years. The WELL EXPANSION module has been used for about one year.

ShipCAM3 has two separate expansion modules, one for developable surfaces and one for compound curved surfaces. The PLATE EXPANSION module is used for developable surfaces and the SHELL EXPANSION module is used for compound curved surfaces.

The PLATE EXPANSION module operates on developable surfaces created by ShipCAM3.

The SHELL EXPANSION development method is based on triangulation of a surface mesh. The surface mesh may be created by ShipCAM3 itself or imported from other programs, including ship design programs, such as FASTSHIP/YACHT or AutoSHIP.

The SHELL EXPANSION program has a fully integrated graphical user interface. The result of a performed shell expansion is immediately displayed on the screen for visual inspection. Atypical expansion takes less than a second to compute.

Unique outputs are a “strain map” and “longitudinal stretching table” which gives data that assists the plate developer to decide if plate development is acceptable and the eventual operator who will form the plate to see whereto apply the greatest force to deform the plate into its desired shape. Figure 4.2.1 is an illustration of the strain map but it unfortunately does not show the usual colors. Shading has been used instead.

The system does not output a hard copy of a detailed plate sketch nor the N/C code. All plate geometry information, including the strain map must be exported to a CAD system for detailing and nesting and to another module for the N/C code. Also, currently the plate seams and butts must be mesh lines or parallel to the three principal planes, Any deviation from this must be done in the CAD system.

In developing a plate, ShipCAM3 only allows the longitudinal mesh lines to change length. It holds the transverse mesh line’s length constant..

4.3 BMT ICONS Limited

BMT is one of the early mainframe computer shipbuilding CAL systems. It was originally developed by the British Ship Research Association and, not surprisingly, was named BRITSHIPS. I.ike all of the early systems it has been continuously improved in all its areas of application. It is a complete shipbuilding CAD/CAM system for producing drawings, material definition, production shop sketches and N/C data It covers hull geometry, structure, piping and outfit It is also integrated with the usual naval architecture and other design systems. A PC version has been offered since 1991. The head office of the BMT group of companies is in Teddington, England. They also have an office in Arlington, Virginia. BMT ICONS Limited is responsible for all software and has its office in Wallsend, England.

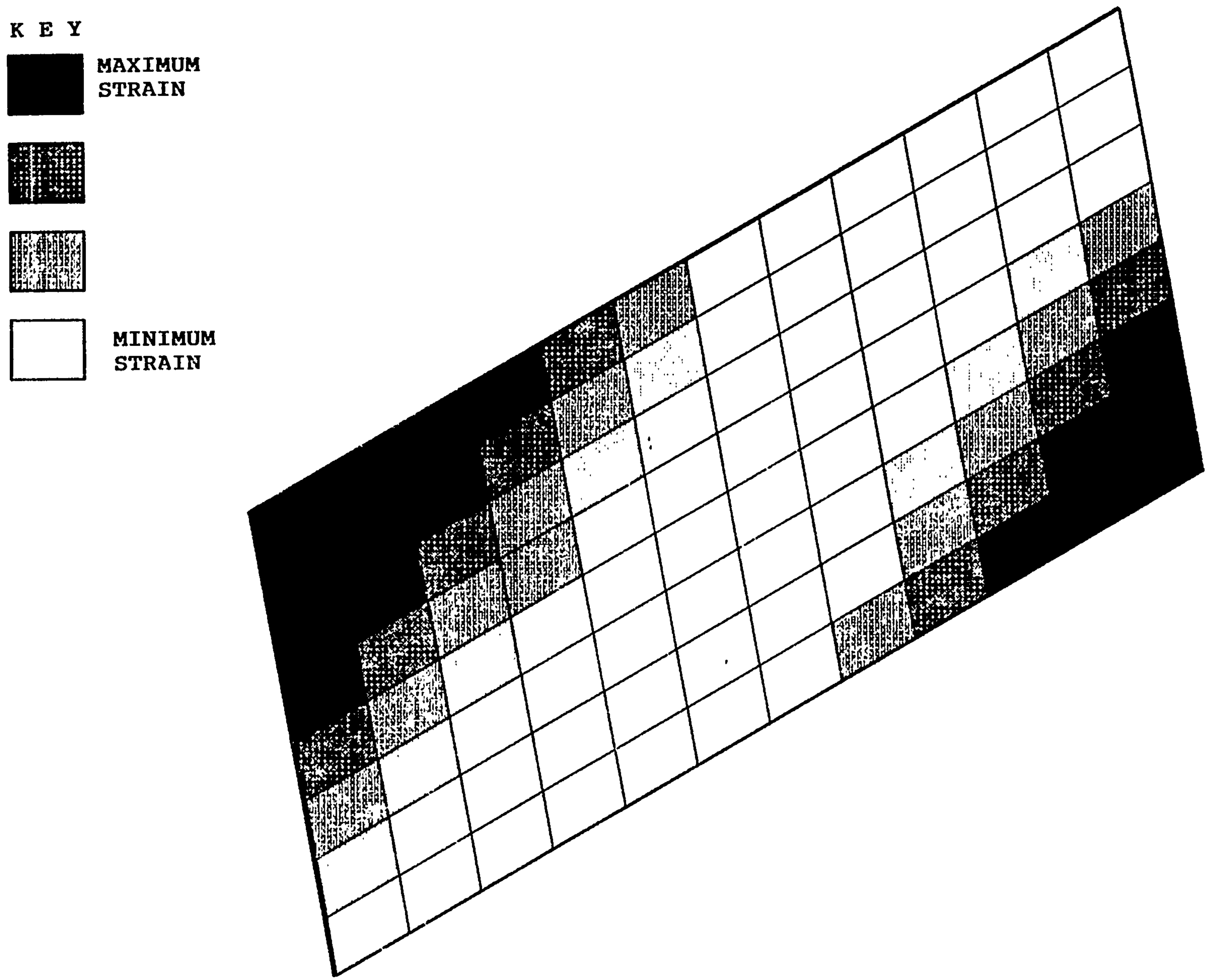


FIGURE 4.2.1 - STRAIN MAP FOR SHELL PLATE

The shell development algorithm is a modified two-dimensional multiple triangulation, approach.which commences at an identified convenient point in the center region of the plate. The algorithm is used progressively and works in general terms up and down to both seams and forward and aft to both butts. Up to eight-sided plates can be handled.

The basic BRITSHELL software has been in practical use for about 20 years. The triangulation process has been recently modified to benefit from the fact that the surface data input from the associated SHELLDEF system are now equi-girthed on frames. Furthermore, spline curve fitting has been introduced for the row, column and diagonal girth calculations, with due regard for frames with associated knuckles.

A three-dimensional surface definition is used as the basis from which to derive the necessary shell plate characteristics. An appropriate net of surface points is used to transfer the plate data to the shell development algorithm.

The user is provided with the ability to assess the fairness of curves on the surface, and the curvature of the local surface itself, so as to identify a convenient plating arrangement which best fits regions of double curvature.

The SHELLDEF system permits the user control over which frames are used to define the net of points. Points up each frame are based on equi-girth distances. Sufficient intermediate frames are automatically introduced so as to give a minimum of ten defining frames. This has been found to be satisfactory for most cases.

Plates are developed with respect to their mid-thickness surface. Negative thicknesses maybe specified as for naval ships where the outside of the plating is the molded line. The net of frames data from SHELLDEF is assumed to represent the molded surface. In BRITSHELL these data are first corrected for the thickness of the material before the development process is commenced.

To begin the triangulation process, a central pair of adjacent frames is identified, with due regard to the position of the knuckle frames, and developed. Next a central row pair is developed. The development process is a triangulation which is based on girths calculated between adjacent points of the net, including a set of diagonals in the two central bands one in the direction of the frames and the other across the frames.

For each triangle processed, the user is warned of possible high aspect ratios of max/min lengths of sides and/or the max/min angles of the triangle. If warnings of such severe triangulation occur then it may be advisable to define additional frames in SHELLDEF (simply by prompting the system to draw them) and to then repeat the plate definition and development

Independent triangulation of the four remaining portions of the plate is then carried out using a method that tends to preserve the overall seam and butt girths for matching of adjacent patches.

The above development process is summarized in Figure 4.3.1 which is a reproduction of Appendix 9.1.2, Figure 4.

The algorithm provides methods to develop frame, waterline and interred structure traces with the shell plate as well as a roll line for each plate. A sight line can optionally be marked, as a production aid, together with frame sets information, for the correct forming of the plate.

The approach also provides checking dimensions for manual verification of the developed plate and its markings when required by a shipyard's Quality Assurance Department as shown in Figure 4.3.2 which is reproduced Figure 6 from Appendix 9.1.2.

4.4 Cali & Associates, Inc.

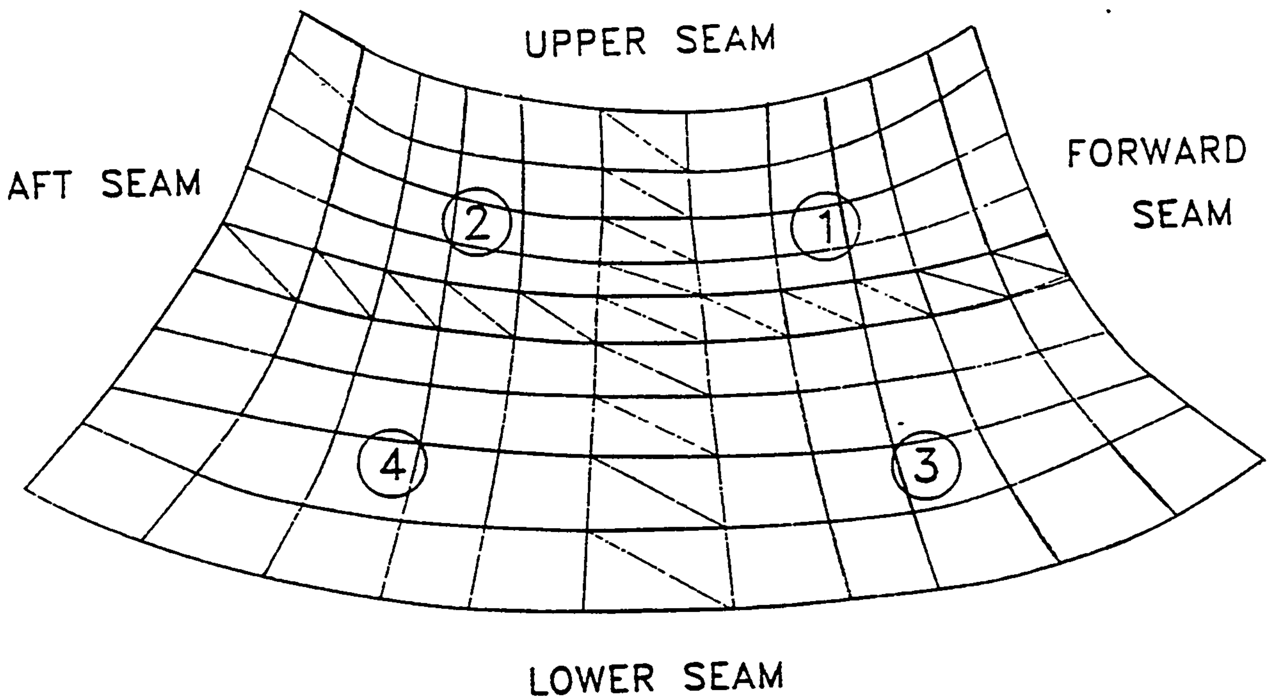
Cali & Associates is the only U.S. developer of a main frame computer shipbuilding CAL system. It was first developed in the late 1960's and has undergone continuous improvement since then into the current SPADES system. It is primarily a structural design and lofting system which is integrated at the design end to the usual naval architectural calculations and at the other end to production / material control.

It has recently been reprogrammed to run on the IBM RISK 6000 work station.

Cali & Associates' office is in Metairie, Louisiana with an associate office in Italy.

SPADES uses two methods for shell plate development, namely the 'Girth Length' and 'Triangulation' techniques.

The Girth Length method would only be used when the majority of the plate is flat and little or no double curvature exists on the curved portion. With this method, the program uses the flat portion as the development plane with all the girth computations from the flat edge towards the tangent curve. The portion of the girth falling on the curved surface is rotated to account for the increased girth in the normal direction, leaving the flat portion undistorted.



Procedure:

1. Define appropriate central frame with regard for knuckled seams.

2. Fit splines to frames and for curves across frames to obtain girth data.

3. Develop first triangle based on calculation of diagonal girth using a local spline fit to data.

4. Develop triangles of central column.

5. Develop triangles of central row.

6-10 Develop regions 1 through 4.

FIGURE 4.3.1 - SKETCH OF THE BMT TRIANGULATION APPROACH

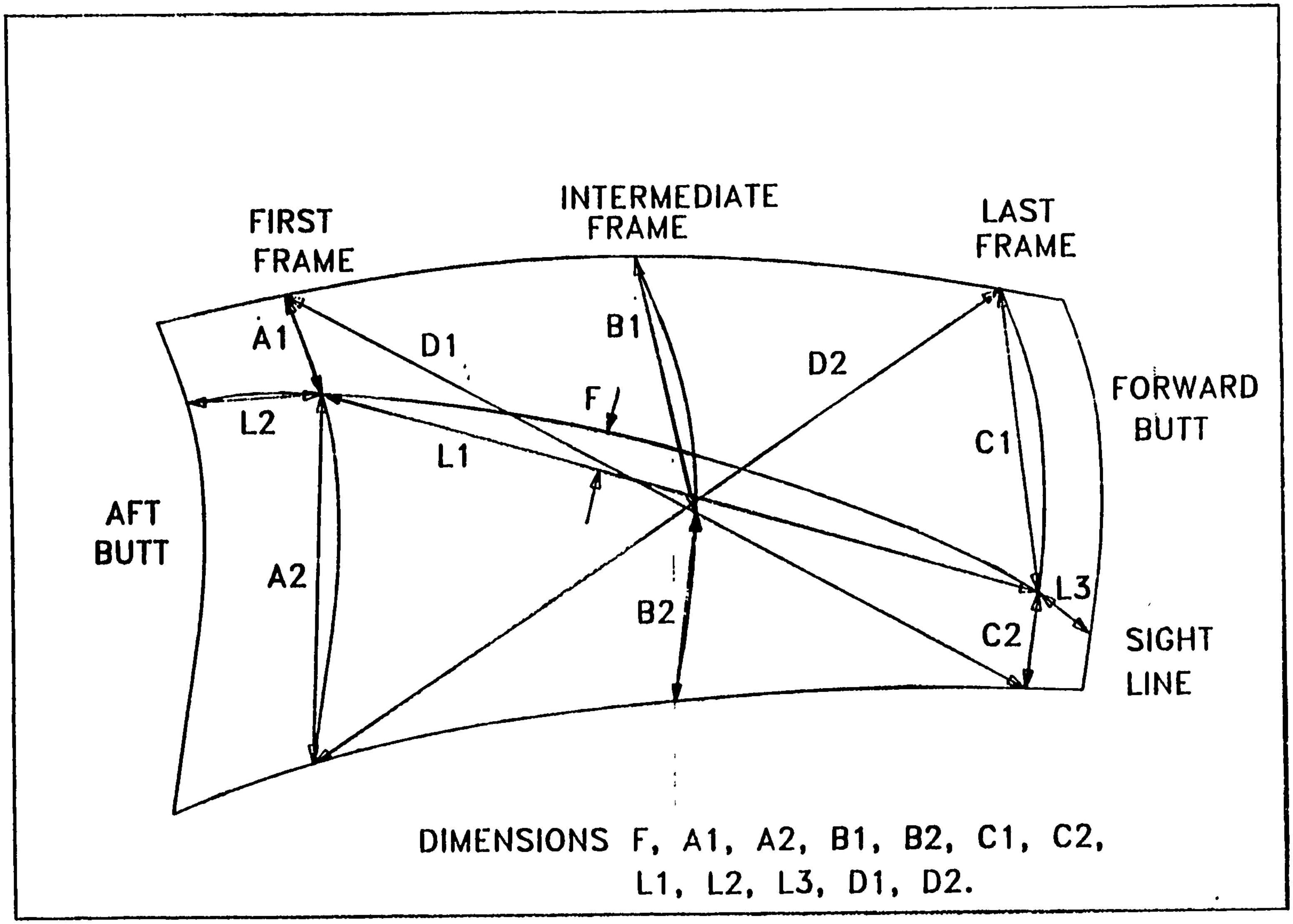


FIGURE 4.3.2 - DEFINITION OF BMT PLATE CHECKING DATA

The Triangulation method is used for alI pIates with double curvature. The program is based on three space points to define a circle, and the girth length is calculated from the circular arc length. The degree of approximation is a function of the amount of curvature in the direction of the diagonal (true girth versus arc girth). The program has a built-in checking routine with warning messages printed during the development, when the cross diagonal yields results with more than one sixteenth of an inch (1/16”) deviation.

The plate development process in SPADES is performed with procedures contained in two modules, namely the ‘Plate Development Module’ and the ‘Part Generation Module’.

The plate development module is limited to a plate with two seams (upper and lower) and two butts which must be parallel to the plane of the frames. Plates that do not have this type of boundary configuration must be developed in the part generation module.

In the part generation module, boundary definition can be contours and/or butts and seams with the plate capable of being subdivided into ‘multi-parts’, each of which can be developed with the same techniques as in the plate development module. The final development is achieved by the combination of the ‘multi-parts’.

The user chooses which method of development should be employed and the system automatically applies the development from the flat or least curved side of the surface to minimize the error propagation. The transverse contour is divided into multi-sections, up to eight (8), to get the best approximation of the diagonaI girth used in triangulation.

The SPADES shell development method is different to the other methods in that it starts the development of the plate at the end of the plate rather than the center. This results in a useful attribute where the user has the option to override the decision made by the system in order to cross check the output of the developed parts for the compound curved plate, by forcing the development from the opposite end of the plate. The two patterns can then be compared for the amount of deviation between them. Where the deviation is significant, excess stock can be provided.

Also in the part generation module, the user has the ability to manually develop the pIate using triangulation techniques consisting of grid definition and manipulating the direction of the development The technique of opposite end development is also used when deemed necessary.

4.5 Coastdesign, Inc.

Coastdesign, Inc. is the developer of the AutoShip and AutoYacht PC based hull design, fairing and lofting system. Both programs were offered on a licence basis in 1986 and the number of users has grown to over 450 worldwide. Coastdesign is Iocated in Surrey, British Columbia

The programs interface with the AutoCAD system providing an integrated design, drawing and lofting system and with the GHS Naval Architecture system for the usual calculations.

Coastdesign uses two programs for shell development, namely AutoPlex and AutoPlate.

The AutoPlex program is based on developable surfaces and must be used at the design stage to generate a hull which may be plated by pure bending and with no stretching or thinning to form the resulting plates.

The AutoPlate program method handles plates to be expanded on any shape of hull and takes into account the strain required to form the plate. The term compound curved is used to describe these types of surfaces which cannot be formed purely by bending. The amount of compound curvature is measurable as gaussian curvature. The geometry of the hull for use in Autoplate is provided by a hull design and fairing program called AutoShip which can either be used to create a hull design or to match the geometry of an existing hull.

Autoplate expands a patch on the hull by a finite element method. The patch is represented by a series of points or nodes on tie hull surface. The length of geodesic paths are measured between adjacent nodes. These geodesic lengths are later used to define the relative positions of nodes in the 2 dimensional case. Since the surface patch may have compound curvature, the link lengths (geodesic distances) must be altered slightly in the 2 dimensional case. The factor by which the link lengths must be changed is equivalent to the strain required to form the 3-dimensional surface from the 2 dimensional starting blank A large number of simultaneous equations must be solved in order to arrive at the nodal positions with their associated strains. This method of plate expansion is protected by U.S. patent laws. It is used by Coastdesign under Iicence from AeroHydro Inc.

The shell plate drawing is not an output from the shell development system. Data must be transferred to AutoCAD to prepare the final useable drawing.

A unique attribute from AutoPlate is a sketch showing strain contours. Like the ShipCAM3 strain map, the strain contour sketch can be used by both the plate developer and ythe operator forming the plate.

4.6 Kockums Computer Systems AB

Kockums Computer Systems is a group branched off Kockums Shipbuilding in Malmo, Sweden. Although Kockums Shipbuilding had developed its own mainframe computer shipbuilding system called STEEBEAR, it acquired the Norwegian AUTOKON system and just recently the German Schiffco computer system. As AUTOKON has been used in the U.S. and Canadian shipyards since 1968, it was selected for this study.

AUTOKON is currently offering a work station version of its system. Like the BMT system, AUTOKON is a ‘total” shipbuilding system covering structure, piping and outfitting and is integrated at the front end with naval architectural calculations and hull shape design.

The shell plate development method uses a 3D model built up by sculptured and planar surfaces. All curves describing the hull of a ship or floating structures are stored in the sculptured surface. Curves can be developed interactively by the user using crosshair points, 3D input points or points picked from other curves.

The shell plates are defined using the same set of commands as for defining plane parts. Commands are used for adding thickness, excess, shrinkage or other auxiliary functions. The user can choose from crosshair pointing on plate corners or interactively typing the limiting seam curves’ names. A shellplate can have a maximum of 99 limiting seams. This means the shellplates can have maximum 99 corners. Marking curves are stored according to user given options. Internal structures as bulkheads, etc., limited by the shell, will consider the plate thickness. Commands are available to calculate the unexpanded plates’ attributes such as area, weight and center of gravity in ship coordinates. Jigg and templates are calculated on user request

Once the plate has been described, the user requests the system to expand the plate. A unique attribute is that the user has the option to develop the plates using longitudinal, transverse, or lateral curves. A rolling line is automatically generated.

Each plate is expanded on a more or less rectangular grid. The grid is defined by expansion curves. The geometry of expansion curves is taken from the 3D model. Expansion curves can be transverse frames, water lines or buttocks. Using the outer contour of the part, the program selects a subset of expansion curves, and then a certain piece of each curve. The arc of this piece is divided into 4 to 20 pieces giving 5 to 21 XYZ points on each curve. The spacing between pairs of expansion curves is then developed by triangulation, giving U-V coordinates, and the patches thus formed are nested together in a plane. During the triangulation the system uses true girth along expansion curves and circular interpolation between curves in the other direction, not just straight lines between points.

XYZ points are 3D points in ship coordinates. W points are 2D local points in the expanded plane. The program computes a set of Coon's patches for the XYZ grid. This enables a mapping from XYZ points to W points for the plate. Such point sets are found for all curves on the plate, and finally planar curves are faired through the point sets, giving the geometry of the expanded part

The system calculates a basis line for the expansion. This line crosses all the expansion curves. The system starts the triangulation and nesting from this curve and works outwards down on pairs of expansion curves. During the nesting process of the expanded patches the system determines the stretch or compression for the plate.

A unique attribute is the classification of plates into Classical (or Traditional) and Specific. Based on this differentiation, the system generates the expansion grid in two very different ways that affects the way plates should be treated in the problem areas.

The 'Classical' plate has 4 edges. Two edges are on expansion curves, that is, butts, and the other two are the classical upper and lower seam. For such a plate, the system selects the expansion Curves between the butts, and uses the arcs of these curves between Iower and upper seam. This is enough to get a good grid system and a correct development

If these requirements are not met, the system uses an extra expansion curve beyond each end of the plate. The user can also tell the system to treat some curves as limitation curves for the grid. For example, when the curve is a knuckle curve (chine).

4.7 Senermar

Senermar is a Spanish Ship Design Consultant headquartered in Madrid. Their FORAN system is a mainframe computer total shipbuilding system covering design to manufacturing in all areas. Their system is unique for a number of reasons.

First, it developed as a computer aided design system, providing the contract design drawings in the late 1960's. It developed overtime into the preparation of the detail design drawings and then into the lofting and manufacturing information area.

Second, it overcomes the fact that the hull surface of a ship is undevelopable in a mathematical sense by approximating the ship hull surface for each plate by a set of analytical developable surfaces. This shell development approach has beeninuse since 1972.

The shell development method is based on a substitution of the hull surface of the ship around the zone of a shell plate by the best fitting mathematically developables surfaces (cylinders and / or cones). The only practical limitation of the algorithm is that the surface of the hull, inside a shell plate, has to be continuous or, in other words, a shell plate must not have knuckles inside the plate boundaries. This means that knuckles must be edges of the pIate.

To obtain a high accuracy each plate is internally broken down into mathematical domains. This is performed automatically and for each domain the adjusted surface parameters are calculated. Then, plate development is obtained as the addition of consecutive domains. This uniquely parallels the way the shell plates are actually processed in the workshops, where press machines and bending rolls are used to form the plates.

In addition to the cutting marking and bending information, other useful values to help manufacturing such as developability index, minimum length of the bending machine, main generatrix position and information for checking both bending and cutting are provided.

The shell plate is defined as an area of the hull of the ship limited by four curves. The two more or less transverse lines will be named as butts and the other two, more or less longitudinal, as seams.

The definition of the plate boundaries is accomplished in an interactive graphic way and their results are stored in a common data base.

A shell panel is defined by the user by selecting graphically the four lines limiting the panel and some general attributes such as panel margins, key of symmetry and assembly / subassembly block assigned to the panel.

Finally, in the shell plate definition process the user indicates the thickness and steel quality, and, optionally the shrinkage factors to be considered when developing the plate.

As **a** result of the shell plate creation the program develops the part, calculates the minimum rectangle circumscribing the developed contour and assigns, automatically, the gross plate that produces minimum scrap according to the plate’s catalogue of the shipyard. If the result is not acceptable, the user has the option of changing the topological definition of seams and butts and recalculating the plate in order to reduce the scrap percentage.

4.8 CAL Developers Shell Plate Method Summary

The six participating CAL developers can be grouped into two PC based and four main frame based systems. However, all the main frame based systems are currently offering stand alone and networked work station versions of their systems.

All systems except Senermar's FORAN use triangulation of many small panels formed by four 3-D space points to obtain the flat developed shape of the plate. However, each uses a slightly different application. Senermar use a unique approach of building up the surface definition for each plate from a number of analytical mathematical surfaces and then developing each one of the set of surfaces and nesting them together to obtain the flat developed shape of the plate. The SPADES system starts its development at one end of the plate whereas all the others start in the middle.

All systems except ShipCAM3 and AutoPlex/AutoPlate automatically take care of plate thickness and its location relative to the molded line.

All programs provide an N/C code output and a hard copy sketch of the developed plate and its marking. However, ShipCAM3 requires the use of an independent CAD system to accomplish this. They all provide manufacturing aid information. ShipCAM3, AutoSHIP and AUTOKON all offer different versions of plate strain information which can be used by the plate developer to help decide if developed plate is acceptable, and by the forming operator to show where the deforming force should be applied and to what extent

Table 4.8.1 presents a summary of the participating CAL developers shell development systems.

TABLE 4.8.1 - PARTICIPATING CAL DEVELOPER SYSTEM DESCRIPTION SUMMARY

COMPANY'S NAME	**ALBACORE RESEARCH**	**BMT ICoNS LIMITED**	**CALI & ASSOCIATES, INC.**
SYSTEM'S NAME	ShipCAM3	BRITSHIPS	SPADES
AVAILABLE SINCE	1990	1966	1973
USER INTERFACE	INTERACTIVE GRAPHICS	INTERACTIVE GRAPHICS	INTERACTIVE GRAPHICS
HARDWARE REQUIREMENTS	PC	MAINFRAME, WORK STATION AND PC	MAINFRAME ANDWORK STATION
DATA INPUT	FROM OFFSETS VIA SYSTEM FAIRING PROGRAM. ALSO FROM OTHER SHIP CAD SYSTEMS.	FROM SYSTEM FAIRING AND HULL SURFACE DEFINITION PROGRAM.	FROM SYSTEM FAIRING PROGRAM
SURFACE MODELLING	MESH USING 4TH ORDER B-SPLINES GENERATES 3D VERTICES ON SURFACE. VERTICES JOINED BY STRAIGHT LINES.	SURFACE DEFINED BY BI-CUBIC B-SPLINE PATCHES. TYPICALLY 50 PATCHES FOR ONE SIDE OF A SHIP'S HULL. A NET OF SURFACE 3D POINTS FOR ALL DEFINED SURFACE CURVES IS USED FOR THE SHELL PLATE DEVELOPMENT. NET POINTS ARE JOINED BY SPLINES.	GRID OF 2-D CURVES (TRANSVERSE AND ARBITARY LONGITUDINAL) PLUS 3-D BOUNDARY CONDITION CURVES
SHELL DEVELOPMENT APPROACH	COSINE LAW SINGLE TRIANGULATION OF STRAIGHT LINES BETWEEN VERTICES. STARTS IN MIDDLE OF PLATE AND DEVELOPS MESH COLUMN (TOWARD SEAMS),THEN SUCCESSIVE MESH COLUMNS TOWARDS BOTH BUTTS. MAINTAINS GIRTH LENGTHS OF MESH CONSTANT AND TAKES ACCOUNT OF ALL DEVELOPMENT DEFORMATION IN LONGITUDINAL DIRECTION.	SINGLE TRIANGULATION FOR EACH SET OF FOUR NET POINTS. STARTS IN THE MIDDLE OF THE PLATE, DEVELOPS TOWARDS THE SEAMS AND THEN ALONG A CENTRAL BAND TOWARD BOTH BUTTS. REMAINING FOUR PORTIONS OF PLATE ARE DEVELOPED IN A WAY THAT TENDS TO MAINTAIN THE OVERALL SEAM AND BUTT LENGTHS TO PRESERVE MATING WITH ADJACENT PLATES	USES BOTH GIRTH LENGTH FOR SIMPLE PLATES AND SINGLE TRIANGULATION FOR COMPOUND CURVATURE PLATES. WORKS FROM PLATE END CLOSEST TO AMIDSHIPS. a GRID OF UP TO 9 BY 50 POINTS IS USED FOR COMPUTING SURFACE DISTANCES BETWEEN POINTS. THE COMPUTED DISTANCES ARE THE USED TO TRIANGULATE THE POINTS INTO THE EXPANDED PLANE. TRIANGULATED POINTS ARE EVENTUALLY CURVE FITTED TO CREATE THE FINAL OUTPUT OF THE PLATE OUTLINE AND ALL INTERNAL LAYOUT.
PLATE MARKING	ONLY MARKS WATERLINES, FRAMES AND BUTTOCKS ON PLATE	ANY DEFINED CURVE/LINE ON SURFACE. ROLL LINE AND SIGHT LINE (OPTIONAL)	ANY DEFINED CURVE/LINE ON SURFACE AND ROLL LINE
UNIQUE ATTRIBUTES	STRAIN MAP. LONGITUDINAL DEFORMATION TABLE.	ABILITY TO ASSESS FAIRNESS OF SURFACE CURVES AND LOCAL SURFACE CURVATURE. PLATE CAN HAVE UP TO 8 SIDES TRIANGULATION ASPECT RATIO VARIATION WARNING. PROVISION OF CHECKING DIMENSIONS. ABILITY TO HANDLE ZERO GIRTH BUTTS. CAN HANDLE 8 SIDED PLATES. INPUT AND OUTPUT UNITS CAN BE DIFFERENT. CAN ADJUST FOR WELD SHRINKAGE	USE OF OPTIONAL REVERSE END DEVELOPMENT AS A CHECK ON NORMAL DEVELOPMENT. EXTENT OF DIFFERENCE CAN BE USED TO DECIDE NEED FOR STOCK. USES OPPOSITE DIAGONAL AS A CHECK ON GRID DISTORTION.
GUIDELINES	MESH SHOULD BE SIZED SO THAT THERE IS ONE VERTEX FOR EACH CURVE FOR EACH 3 DEGREE CHANGE IN DIRECTION		
TIME FOR TYPICAL PLATE DEVELOPMENT	1 SECOND	LESS THAN 1 MINUTE	

TABLE 4.8.1 (CONTINUED)

COMPANY'S NAME	COASTDESIGN, INC.	KOCKUMS COMPUTER SYS. AB	SENERMAR
SYSTEM'S NAME	AutoSHIP	AUTOKON	FORAN
AVAILABLE SINCE	1972	1968	1972
USER INTERFACE	INTERACTIVE GRAPHICS	INTERACTIVE GRAPHICS	INTERACTIVE GRAPHICS
HARDWARE REQUIREMENTS	PC	MAINFRAME WORK STATION	MAINFRAME WORK STATION
DATA INPUT	FROM HULL DESIGN AND FAIRING SYSTEM PROGRAM	FROM SYSTEM DESIGN AND FAIRING PROGRAM	FROM SYSTEM DESIGN AND FAIRING PROGRAM
SURFACE MODELLING	USES 1ST, 2ND AND 3RD ORDER B-SPLINES IN TRANSVERSE DIRECTION AND CUBIC POLYNOMIAL SPLINES IN LONGITUDINAL DIRECTION.	3D MODEL OF SHIP'S HULL CONSISTING OF SCULPTURED AND PLANAR SURFACES. SCULPTURED SURFACE STORED AS MESH OF LINES	3D MODEL OF SHIP HULL CONSISTING OF PARAMETRIC SURFACES
SHELL DEVELOPMENT APPROACH	AUTOPLEX DEVELOPABLE SURFACE PROGRAM DETERMINES RULE LINES BETWEEN LONGITUDINAL KNUCKLE CURVES. AUTOPLATE FOR COMPOUND CURVATURE PLATES USES A PATENTED FINITE ELEMENT METHOD TO EXPAND SURFACE PATCHES WHICH ARE REPRESENTED BY 3D POINTS OR NODES. THE GEODESIC CURVE LENGTH (GEODESIC CURVE IN 3D IS STRAIGHT LINE IN 2D) BETWEEN NODES AND USES IT IN A SILIMAR WAY TO SINGLE TRIANGULATION.	USES GRID OF EXPANSION CURVES AND CROSSING CURVES. EXPANSION CURVES ARE SEGMENTED INTO 4 TO 20 PARTS GIVING 5 TO 21 3D POINTS ON EACH EXPANSION CURVE. PATCH OF PLATE BETWEEN EACH EXPANSION CURVE AND EACH CROSSING CURVE IS DEVELOPED BY TRIANGULATION USING TRUE GIRTH LENGTH ON THE EXPANSION CURVES AND CIRCULAR INTERPOLATION BETWEEN OTHER CURVES. OBTAINS 2D POINTS FOR DEVELOPED PLATE VIA COON'S PATCHES FOR 3D GRID	TRANSFERS HULL SURFACE FOR EACH PLATE INTO SETS OF DEVELOPABLE SURFACES (CYLINDERS AND CONES). USES NET OF 65 POINTS DETERMINED BY INTERSECTION OF 13 TRANSVERSE CURVES AND 5 LONGITUDINAL CURVES. FIRST CHECKS FOR CYLINDRICAL FIT OF SURFACE. IF NOT ACCEPTABLE FITS TWO CONIC SURFACES WITH COMMON GENERATRIX. CHECKS MEAN SQUARE ERROR AND DEVIATION BETWEEN REAL AND ADJUSTED SURFACES. MAY SELECT MORE THAN TWO CONIC SURFACES IF VALUE OF GAUSSIAN CURVATURE IS GREATER THAN A PREDETERMINED VALUE. THIS ALL OCCURS AUTOMATICALLY BASED ON MANY YEARS OF EXPERIENCE WITH THE SYSTEM.
PLATE MARKING		ANY DEFINED CURVE/LINE ON SURFACE AND ROLL LINE	ANY DEFINED CURVE/LINE ON SURFACE AND ROLL LINE
UNIQUE ATTRIBUTES	STRAIN MAP	USER OPTION TO SELECT DIRECTION AND NUMBER OF EXPANSION CURVES. CAN HANDLE PLATES CROSSING CENTER LINE. CAN HANDLE UP TO 99 SIDED PLATES. CAN ADJUST FOR WELD SHRINKAGE. CALCULATES STRETCH AND COMPRESSION IN FORMED PLATE.	CAN HANDLE BUTTS THAT ARE NOT PARALLEL TO FRAME LINES. CAN ADJUST FOR WELD SHRINKAGE.AUTOMATICALLY REORIENTS PLATES IN WAY OF FLAT OF SIDE AND BOTTOM TANGENCY LINES TO AVOID HIGHVALUES OF DERIVATIVES OF 3D POINT CONVERSION TO 2D POINTS.PRODUCTION AIDS SUCH AS FLAG TO SHOW IF PLATE CAN BE CUT WITH PARALLEL TORCHES. CHECKING DIMENSIONS AUTOMATICALLY GIVEN TO IMPROVE PLATE USAGE DURING INTERACTIVE PROCESS.
GUIDELINES			
TIME FOR TYPICAL PLATE DEVELOPMENT	10 MINUTES	5 TO 45 SECONDS	5 TO 15 SECONDS

5.0 CAL SHELL PLATE DEVELOPMENT LIMITATIONS

5.1 General

U of the participating CAL developers were requested to report limitations of their shell development system. Again, these are reproduced in Appendix 9.1. Specifically, they were asked to report on shell plate limitations such as

Maximum or minimum length
Maximum or minimum width
Plate thickness
Maximum backset
Minimum curvature in any direction
Limit of twist
Ratio of backset to length
Ratio of curvature to width
Ratio of minimum curvature to plate thickness

As it turned out the items suggested in the above list were not limitations for most of the CAL systems.

5.2 CAL Developers Shell Plate Limitation Summary

The following description highlights identified limitations.

Albacore have no known limitations. However, they do point out that their system has only been in use a few years. In addition, their system does not currently automatically take plate thickness relative to molded line into account

BMT also has no real system limitations. Actual shipyard installation capabilities are dictated by the available material size and handling/processing capabilities of the shipyards rather than their system. Based on this experience these "practical limitations" are

Maximum length	66 feet
Maximum width	16 feet
Maximum back set	1.5 inches for rolled plates

BMT also points out that special treatment must be given to soft nose stem and transom plates due to their basic shell development approach rather than degree of "difficulty" of the plate shape.

Coastdesign point out that the AutoPlex system is only for developable surfaces and thus cannot handle reverse double curvature plates such as a flared bow even in a hard chine hull form. Also, that chines must be plate boundaries.

The AutoPlate system is unable to give a rolling line because of the development approach and it cannot develop a plate with more than 4 sides. It cannot automatically add stock, and plate thickness is not taken into account

The AUTOKON system limitations are only in the area of number of expansion curves and the number of subdivisions for each expansion curve. However, these are well beyond the needs of any shell plate.

FORAN has two limitations. The first is for spherical surfaces of small radius. However, it can be handled by dividing the plate into two smaller plates. The second is concerning the angle between the transverse tangents at the upper and lower seams. If it is greater than 90 degrees the plate must be divided into two plates by adding a seam. It is possible to join the two developed parts of the plate by nesting and avoid cutting the added seam.

Table 5.2.1 presents a summary of the limitations of the participating CAL developers shell development systems as reported by them.

TABLE 5.2.I - LIMITATIONS OF PARTICIPATING CAL DEVELOPERS SHELL DEVELOPMENT SYSTEM SUMMARY

COMPANY'S NAME	ALBACORE RESEARCH	BMT ICoNS LIMITED	CALI & ASSOCIATES, INC.	COASTDESIGN, INC.	KOCKUMS COMPUTER SYS. AB	SENERMAR
SYSTEM'S NAME	ShipCAM3	BRITSHIPS	SPADES	AutoSHIP	AUTOKON	FORAN
SYSTEM'S LIMITATIONS						
MAX/MIN LENGTH		66FEET/3FEET			100FEET/ -	
MAX/MIN WIDTH		16FEET/3FEET			100FEET/ -	
PLATE THICKNESS						
MAX BACK SET						
MIN CURVATURE						
LIMIT OF TWIST						
BACK SET/LENGTH						
CURVATURE/WIDTH						
MIN CURV/PLATE THK						
OTHER	USES MESH LINES AS PLATE BOUNDARIES DOES NOT HANDLE PLATE THICKNESS AUTOMATICALLY CAN ONLY MARK WATERLINES, FRAMES AND BUTTOCKS. DECKS WITH CAMBER/SHEER AND LONGITUDINALS CANNOT BE MARKED NO ROLL LINE, ROLL SETS OR PIN JIG CAPABILITY MUST BE TRANSFERED TO A CAD SYSTEM FOR DETAILING ONLY ADDS STOCK TO BUTTS. NO CAPABILITY TO ADD STOCK TO SEAMS	SYSTEM BASED ON BUTTOCK VIEW DEFINITION OF SHELL PLATE. THEREFORE, CURRENTLY, SOFT NOSE STEM AND TRANSOM PLATES REQUIRE INTERMEDIATE MANIPULATION	MAXIMUM OF 8 SEGMENTS PER TRANSVERSE CURVE SHELL PLATES LIMITED TO TWO SEAMS AND TWO BUTTS. PLATES WITH MORE BOUNDARIES OR WITH BUTTS THAT ARE NOT PARALLEL TO FRAMES MUST BE DEVELOPED IN PART GENERATION PROGRAM	DOES NOT HANDLE PLATE THICKNESS AUTOMATICALLY DOES NOT ADD STOCK DOES NOT HANDLE PLATES WITH MORE THAN FOUR BOUNDARIES MUST BE TRANSFERED TO CAD SYSTEM FOR DETAILING NO ROLL LINE, ROLL SETS OR PIN JIG CAPABILITY	MAXIMUM NUMBER OF EXPANSION CURVES IS 100 MINIMUM OF 4 AND MAXIMUM OF 20 SEGMENTS PER EXPANSION CURVE	SMALL RADIUS SPHERICAL SURFACES MUST BE DIVIDED INTO SMALL PLATES PLATES WITH EXCESSIVE CURVATURE IN TRANSVERSE DIRECTION SUCH THAT ANGLE BETWEEN TRANSVERSE TANGENTS AT UPPER AND LOWER SEAMS ARE GREATER THAN 90 DEGREES MUST BE SPLIT INTO TWO PLATES BY ADDING A SEAM

6.0 SELECTION OF FIVE TEST CASES FOR PHASE II OF PROJECT

6.1 General

In the Proposa.I and the Subcontractors' Technical Specifications for Phase I, five areas of a ship's hull that can be considered "problem" or "difficult" shell plates, from the point of view of successful development, were identified. The intent is to actually have the six participating CAL developers develop identical shell plates representing these "difficult" areas in Phase II of this project

While it would be possible to generate five new hypothetical plates, it was considered beneficial to the project to invite the participating CAL developers to propose existing shell plates from their inventory that matched the required test cases. Any such offer had to be made on the understanding that the offered test cases couId be given to all other participants for them to develop each one. Because of this requirement, one of the participants was unable to offer to supply the test cases. Two others chose not to propose any. Three of the participants offered shell plate exampIes for the test cases.

There is no intent to evaluate any of the Phase II development results. The resulting data will simply be presented for review and use by interested readers.

6.2 Description of Required Test Cases

The participating CAL developers' reports confirmed the early definition of 'difficult' shell plate regions on a ship's hull. Five test case shell pIates were identified in the Phase I Proposal and the Subcontractor Technical Specifications. They are shown in Figures 6.2.1 through 6.2.3.

Case 1 is a plate in the region where the normal hull shape in the bow transitions into the top of a bulbous bow. It involves reverse double curvature and twist

Case 2 is a plate in way of the top of a single screw aperture. It involves more than 4 sides, both reverse and regular double curvature and twist

Case 3 is a plate in way of the hull shoulder close to the flat of side tangency curve. It only involves double curvature.

Case 4 is a plate where the upper seam is the erection seam and is in the horizontal plane to suit block construction. It involves double curvature and twist

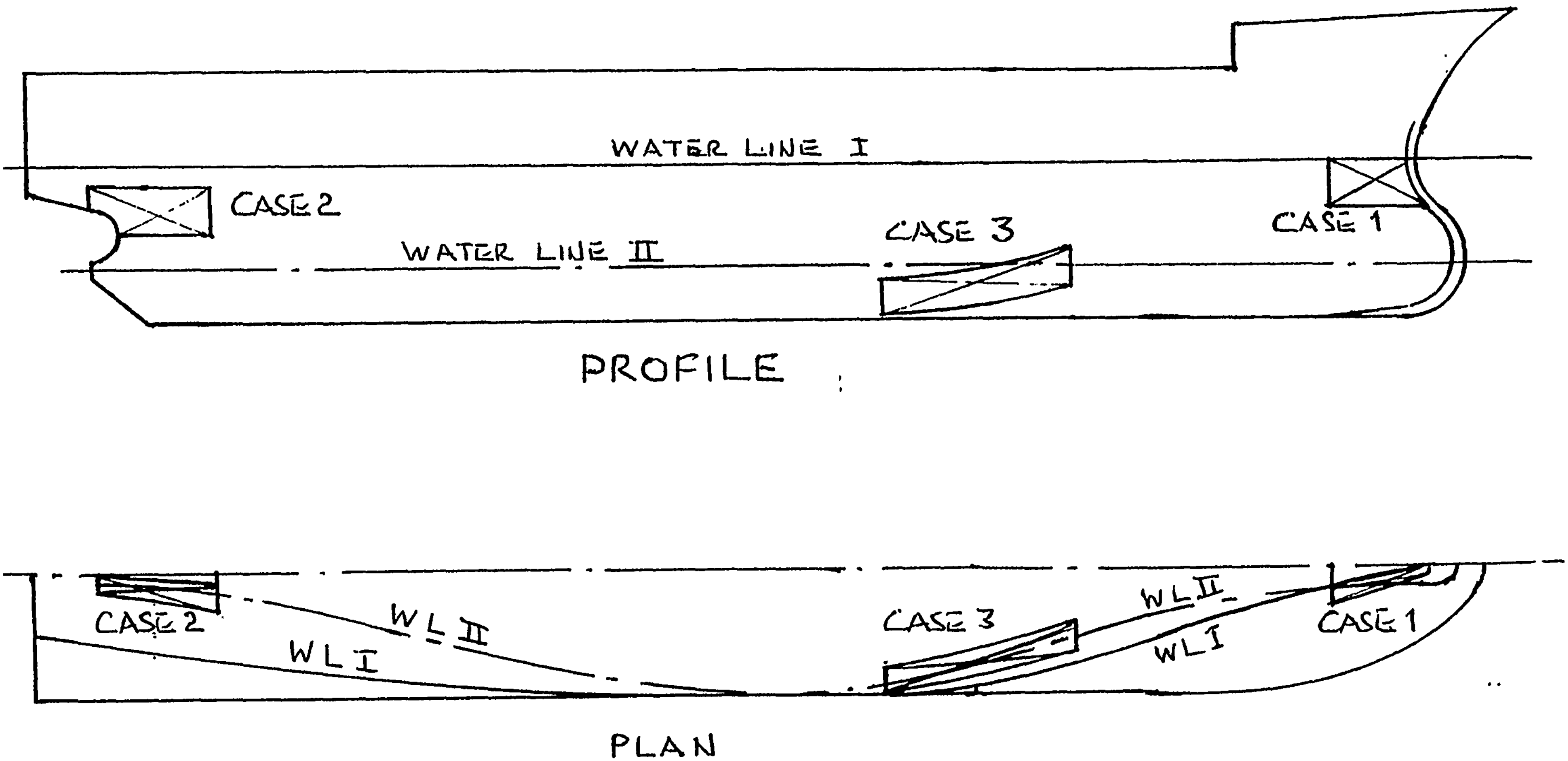
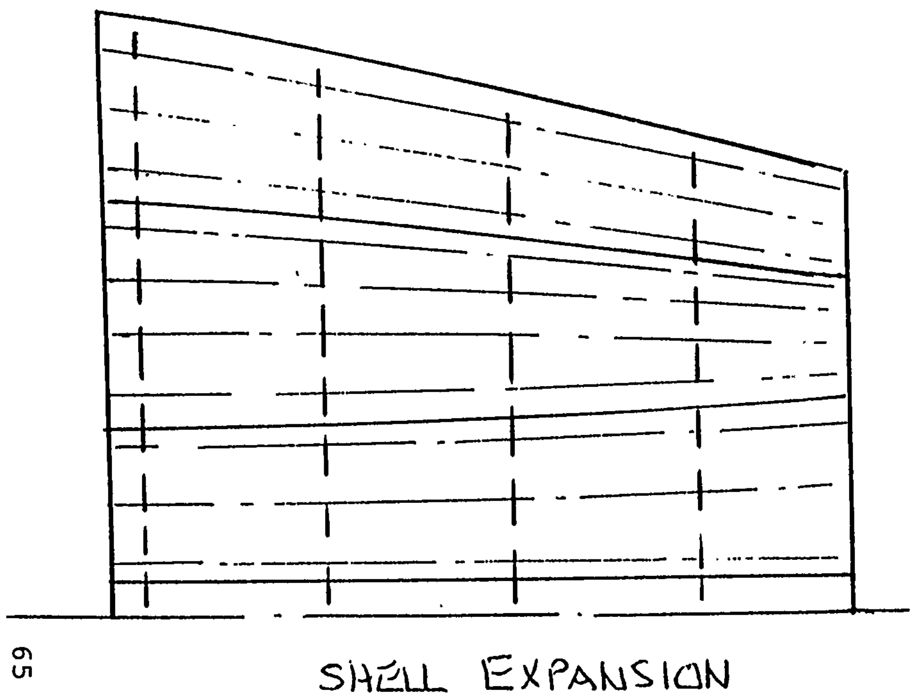
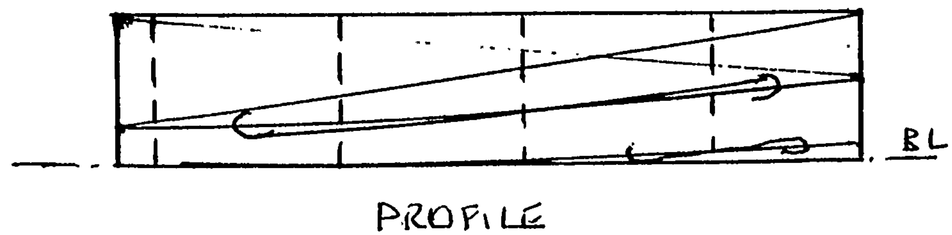
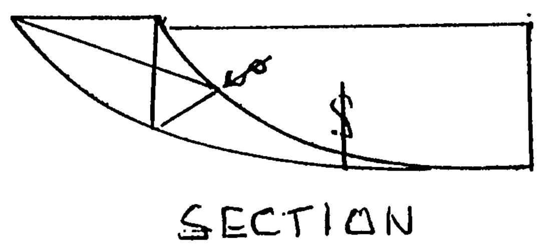
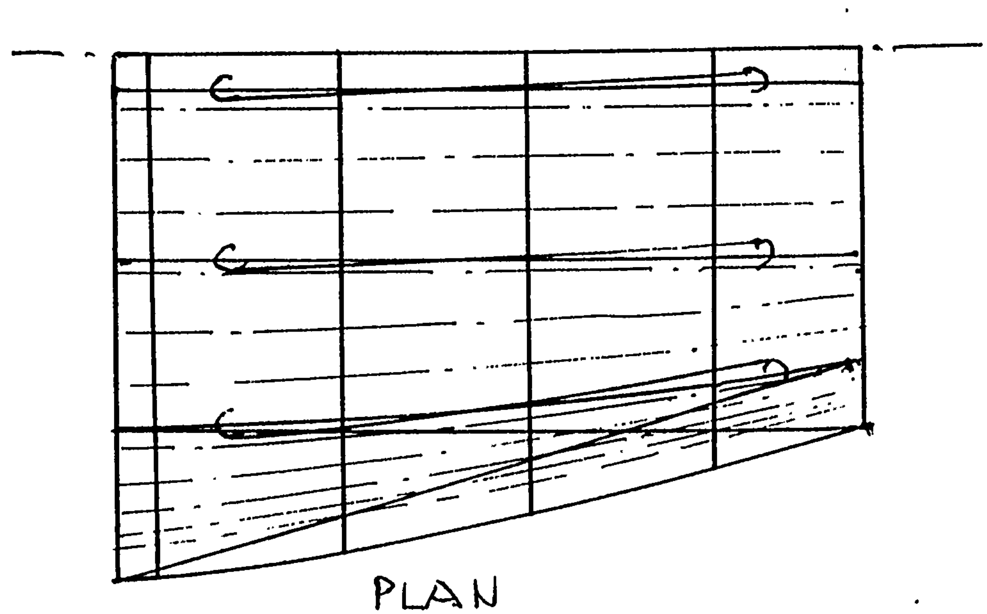


FIGURE 6.2.1 - SHELL PLATE TEST CASES 1, 2 & 3









CASE 4 TOP SHELL PLATE OF BOTTOM BLOCK

Many blocks are configured with horizontal joining seam to assist erection alignment. This results in a severely shaped and formed top plate as shown cross hatched.

FIGURE 6.2.2 - SHELL PLATE TEST CASE 4

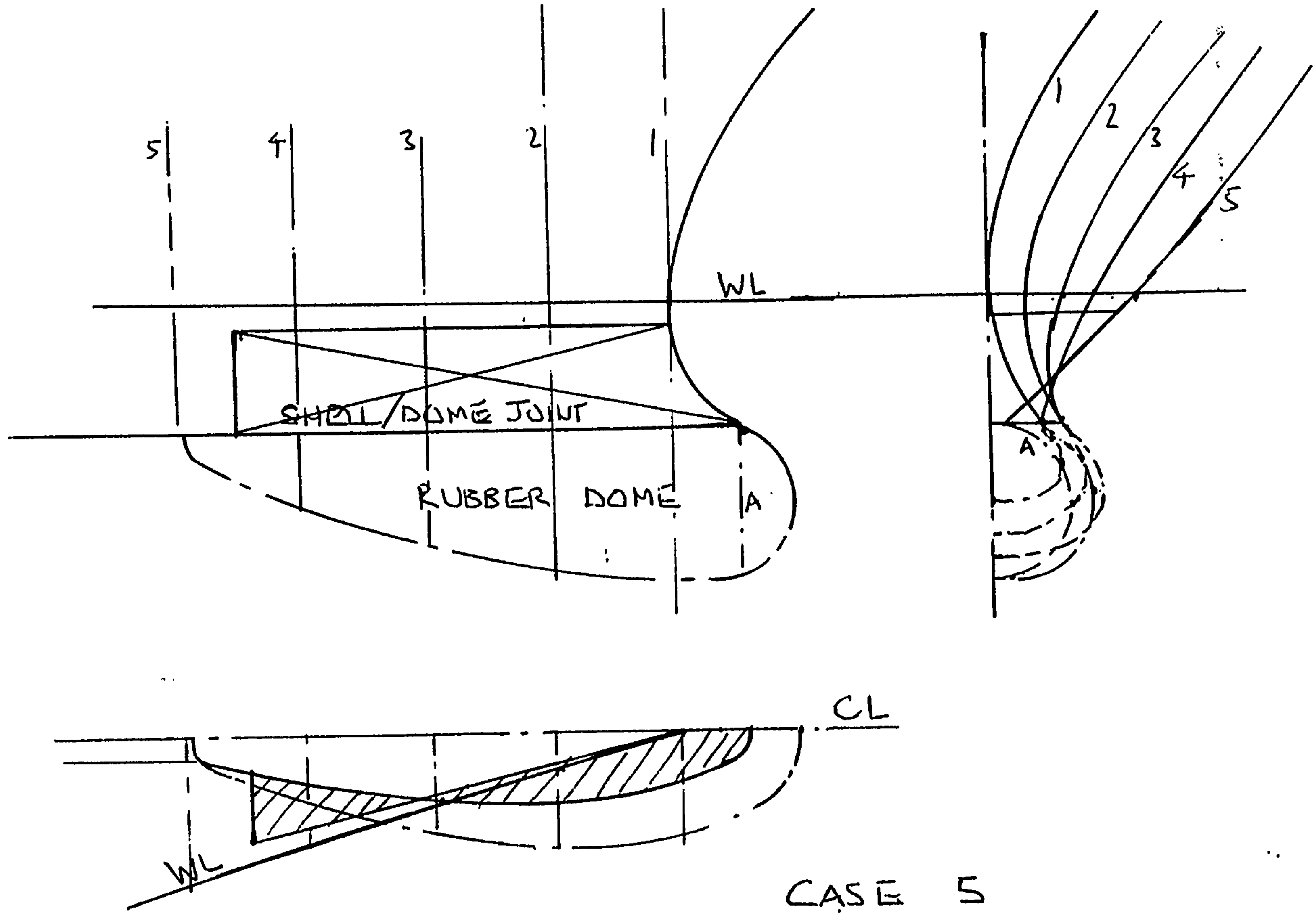


FIGURE 6.2.3 - SHELL PLATE TEST CASE 5

. Finally, Case 5 is a plate which is adjacent to the underhung faired, bulbous bow, sonar dome found on many current warships. It also involves reverse double curvature and twist

6.3 Description of Selected Test Cases

The shell plating examples submitted by BMT were considered to be the most complete and best matched the required test cases.

Figures 6.3.1 through 6.3.12 show the selected test cases.

[redacted]

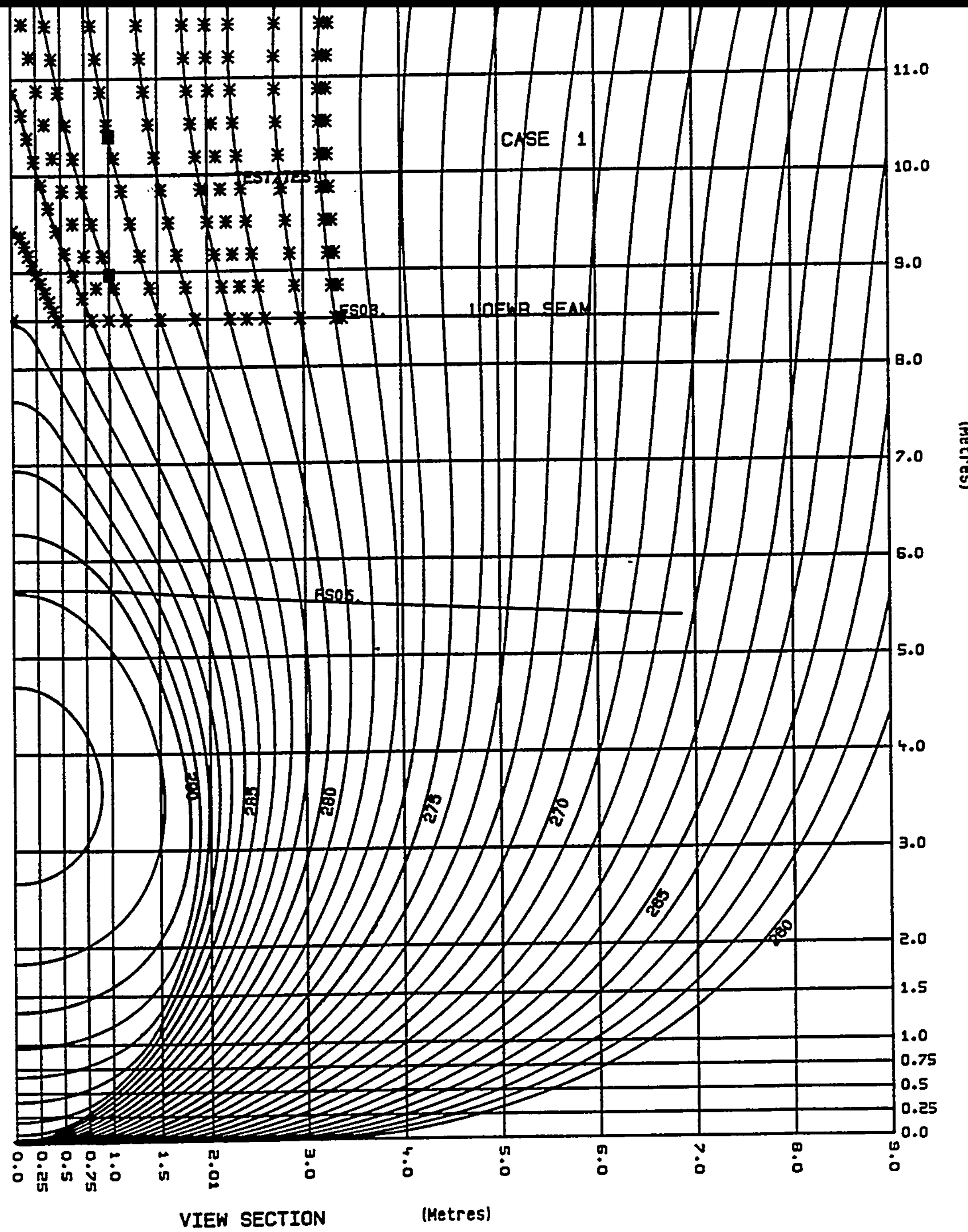


FIGURE 6.3.1 - SELECTED TEST CASE 1 - SECTIONS

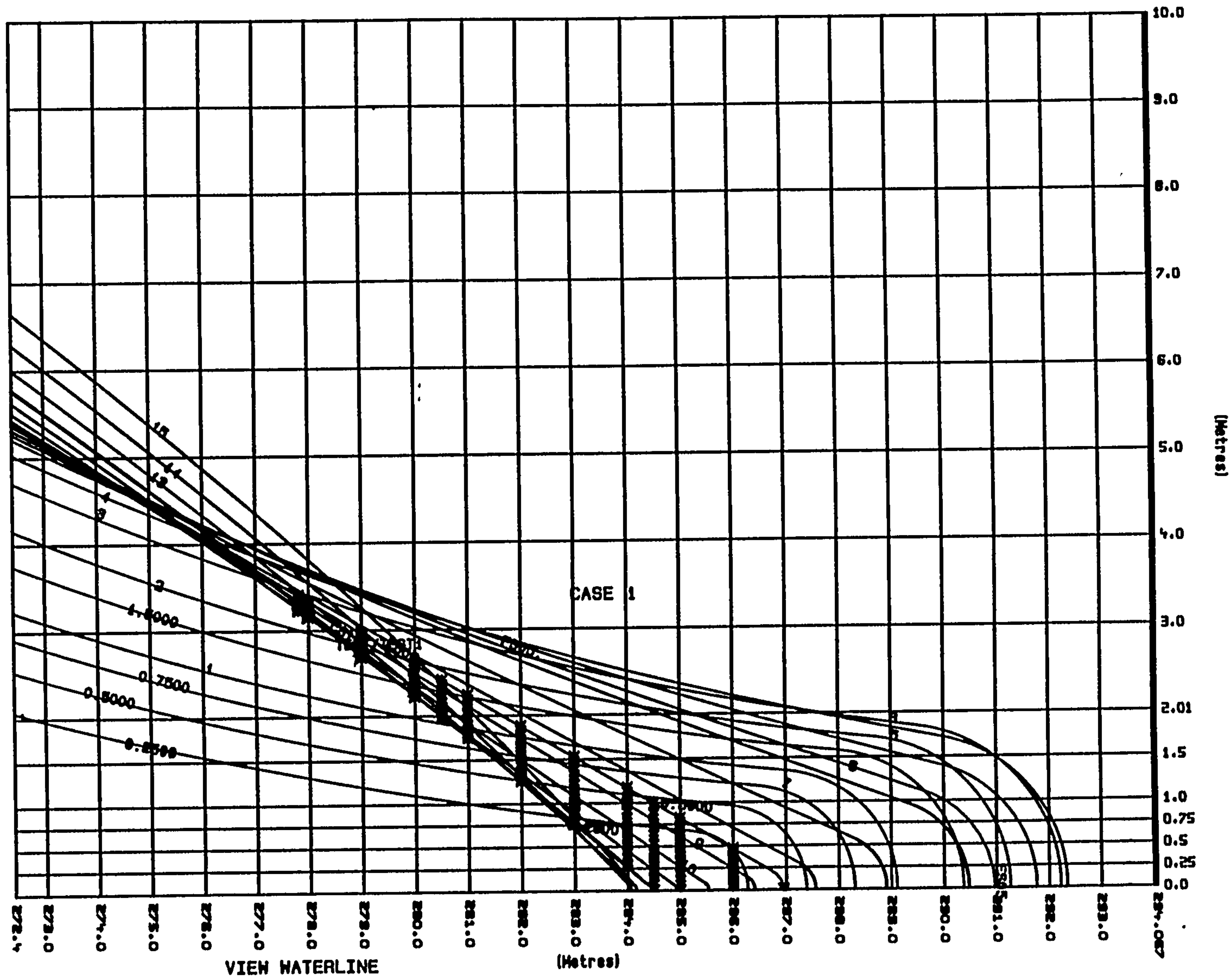


FIGURE 6.3.2 - SELECTED TEST CASE 1 - WATERLINES

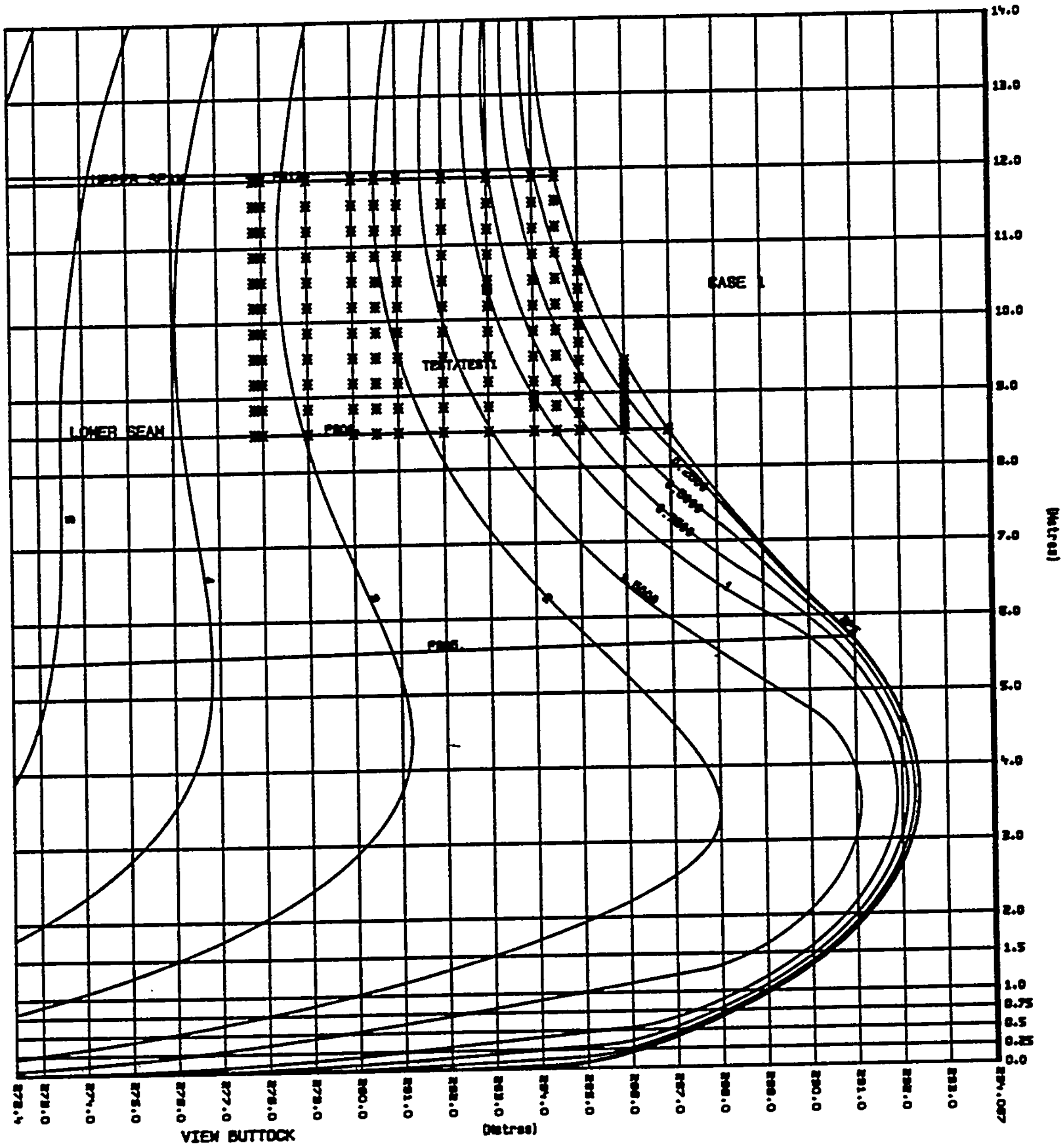


FIGURE 6.3.3 - SELECTED TEST CASE 1 - BUTTOCKS

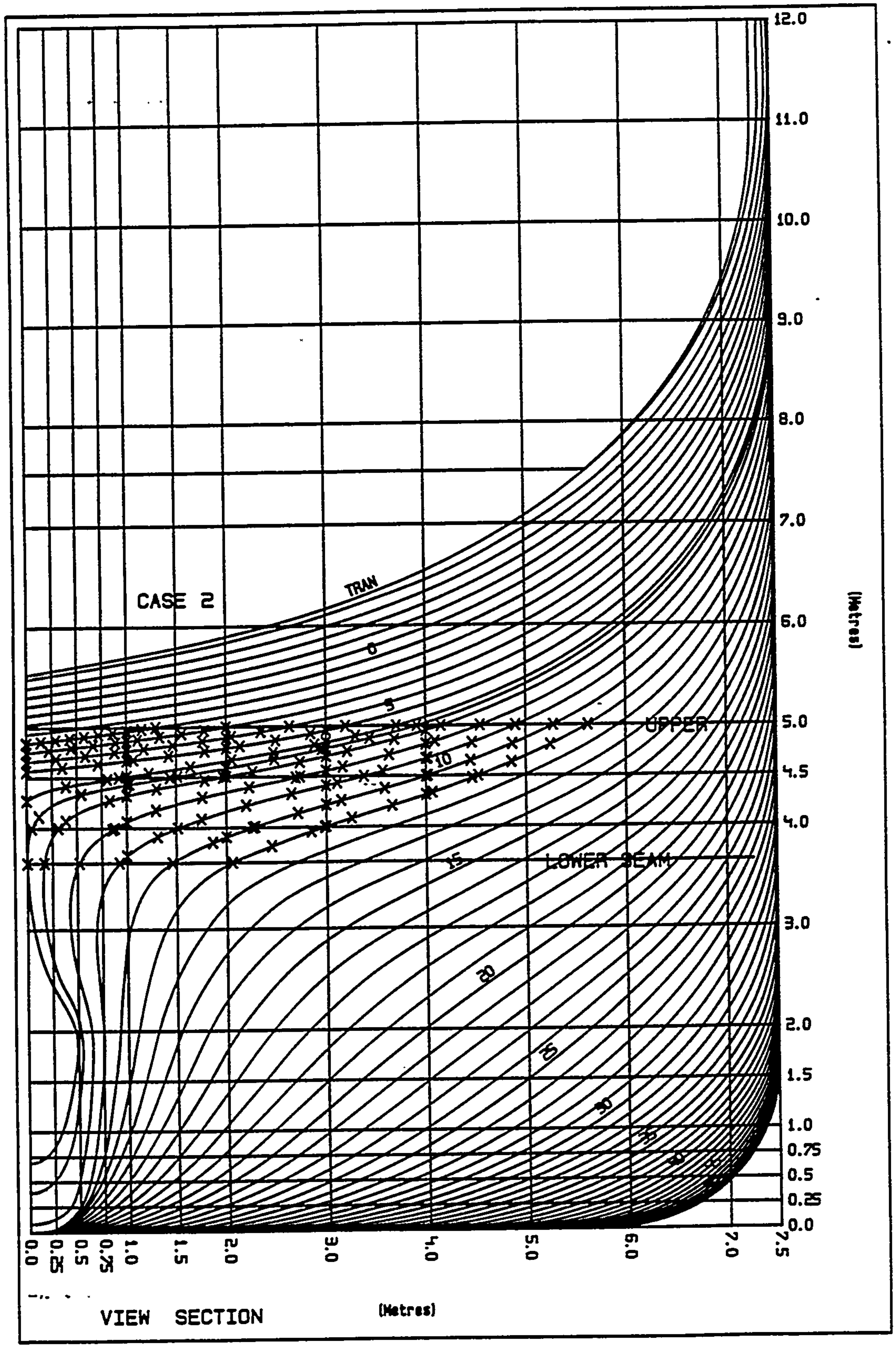


FIGURE 6.3.4 - SELECTED TEST CASE 2 - SECTIONS

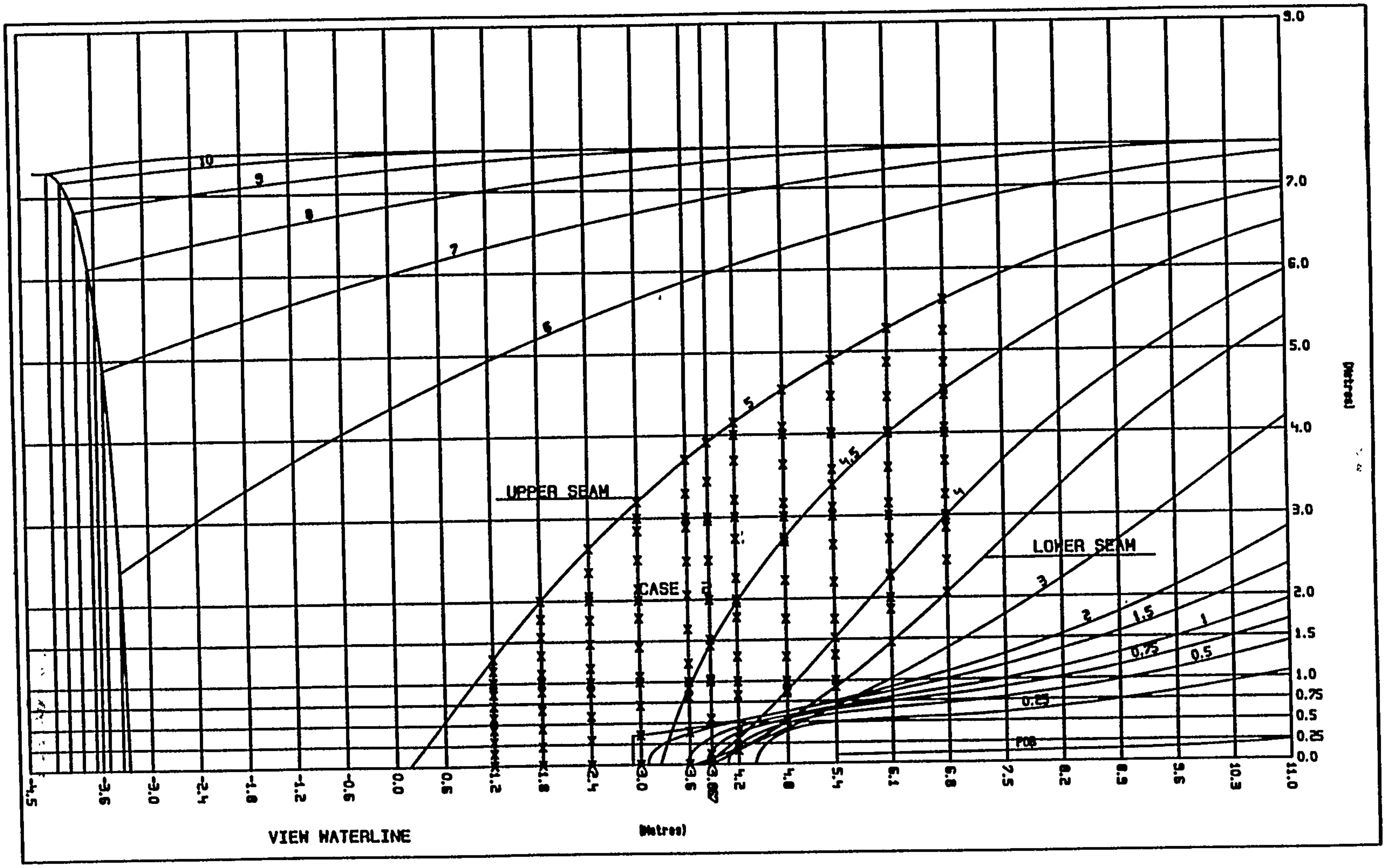


FIGURE 6.3.5 - SELECTED TEST CASE 2 - WATERLINES

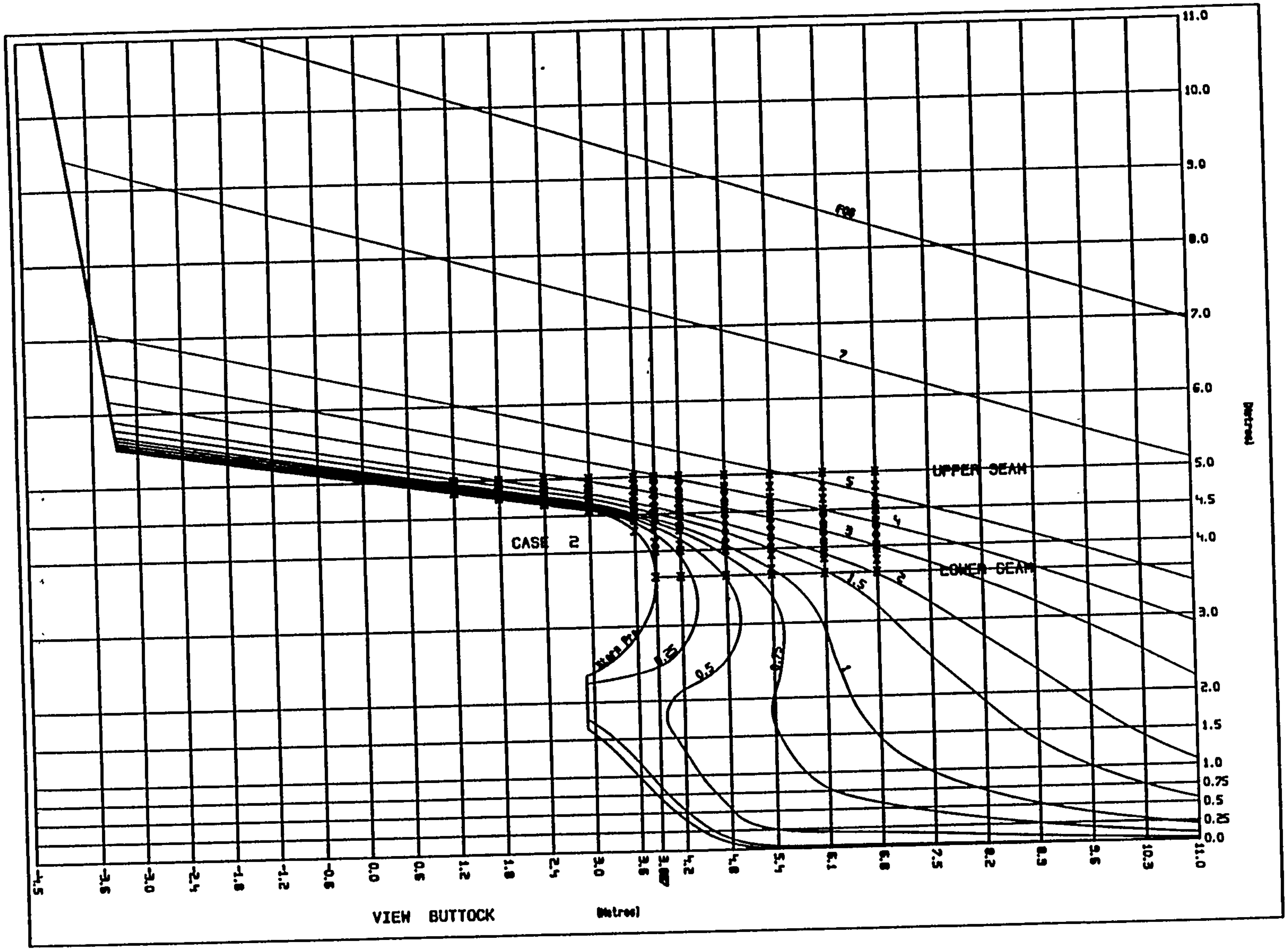


FIGURE 6.3.6 - SELECTED TEST CASE 2 - BUTTOCKS

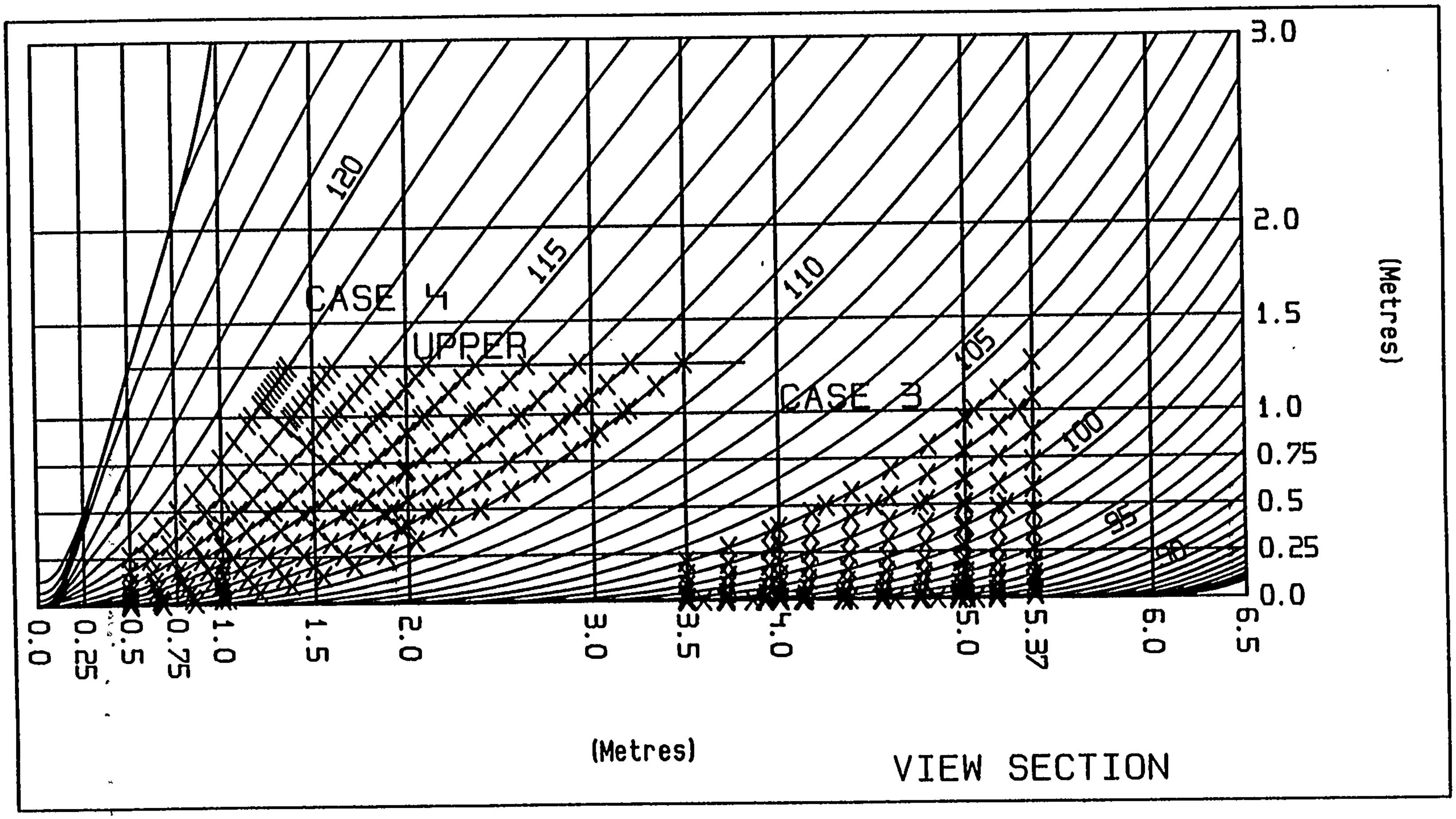


FIGURE 6.3.7 - SELECTED TEST CASES 3 & 4 - SECTIONS

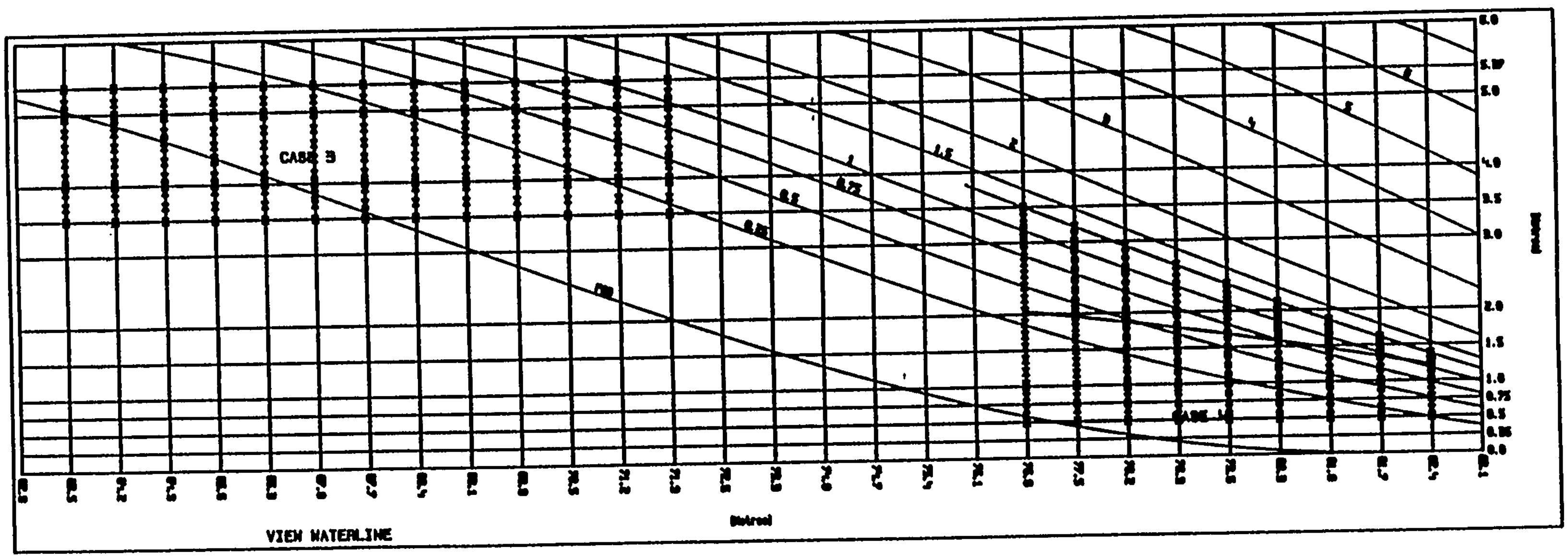


FIGURE 6.3.8 - SELECTED TEST CASES 3 & 4 - WATERLINES

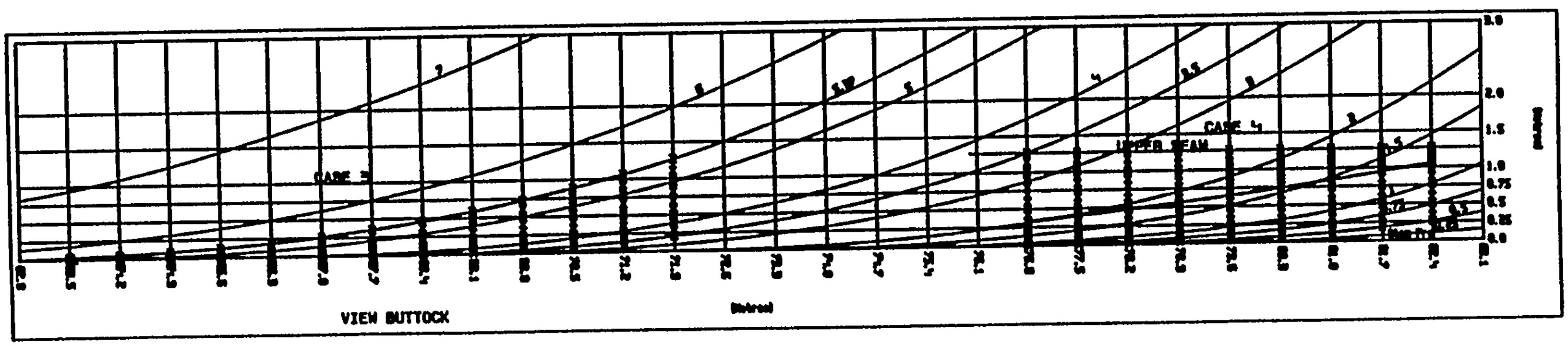


FIGURE 6.3.9 - SELECTED TEST CASES 3 & 4 - BUTTOCKS

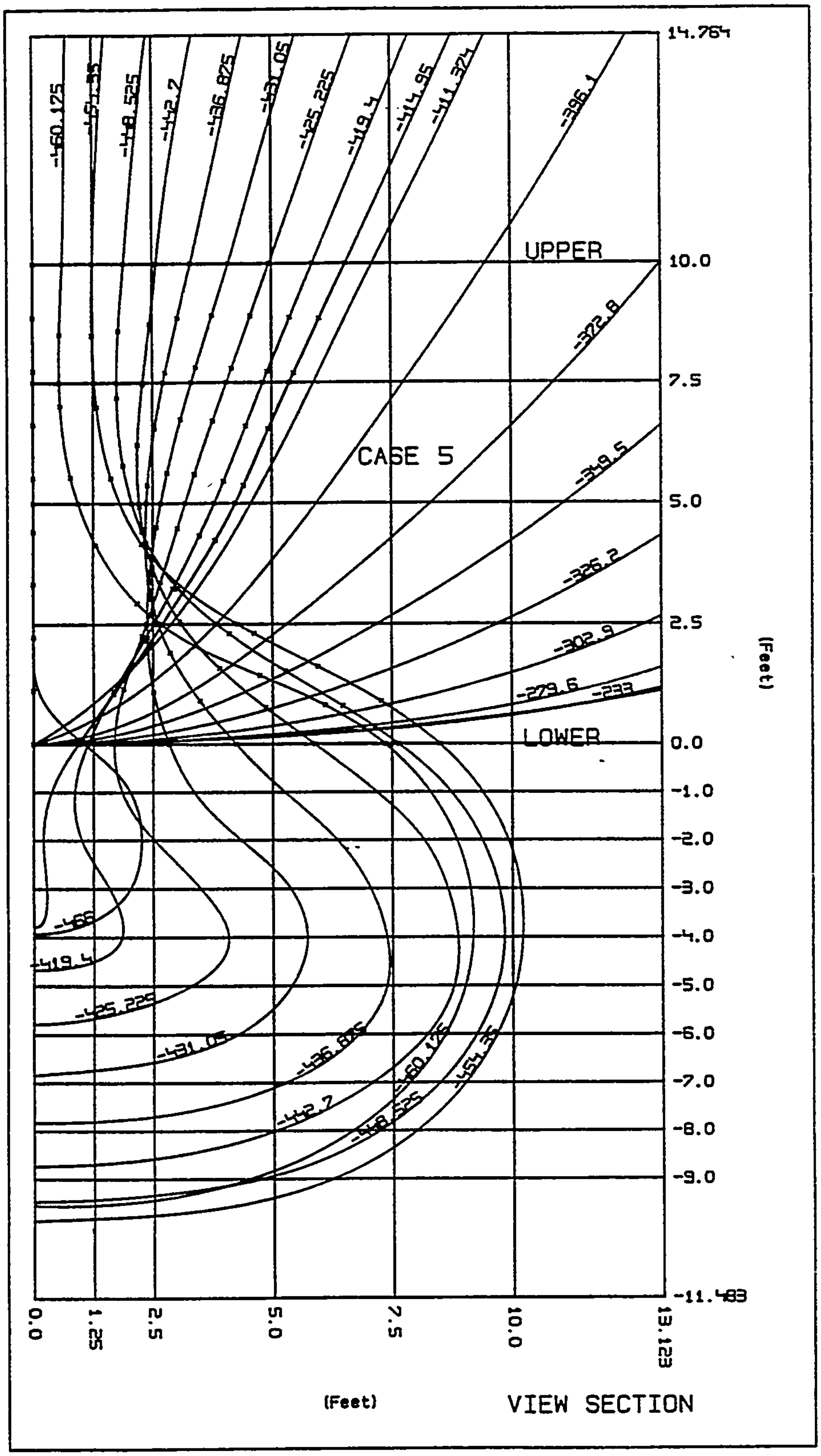


FIGURE 6.3.10 - SELECTED TEST CASE 5 - SECTIONS

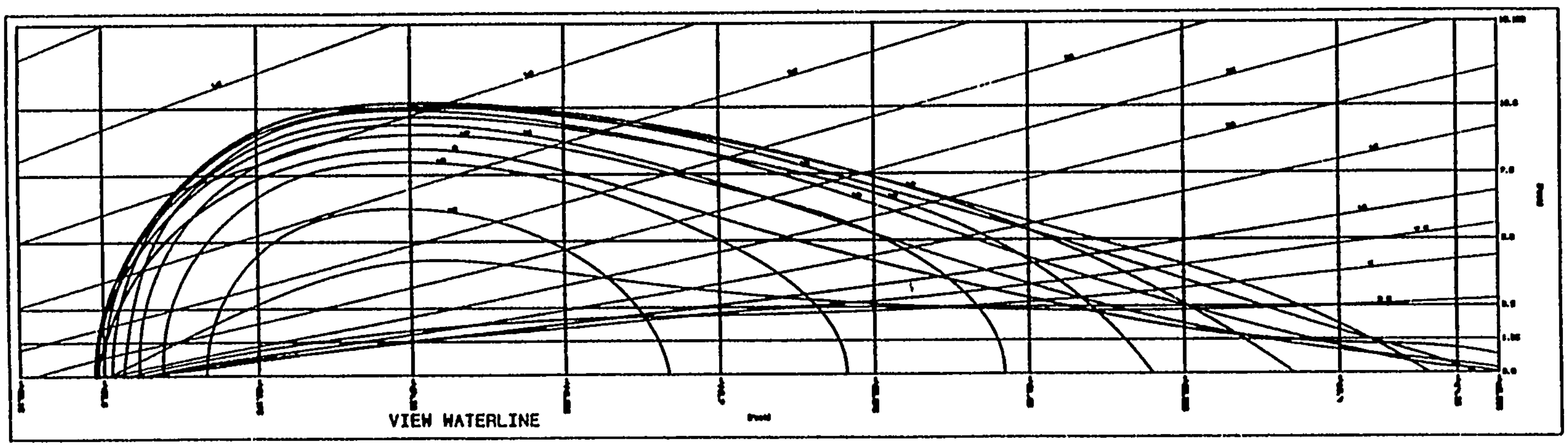


FIGURE 6.3.11 - SELECTED TEST CASE 5 - WATERLINES

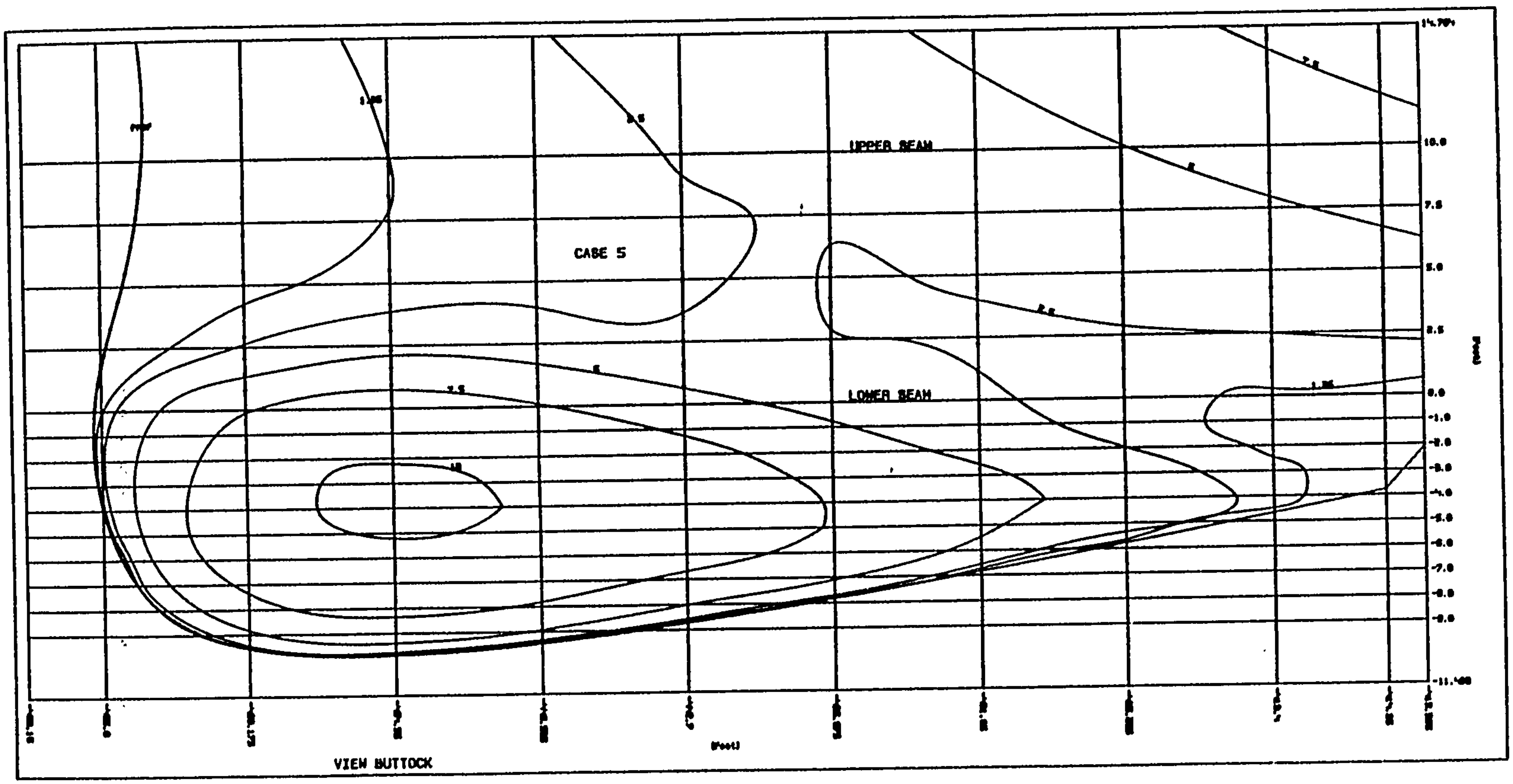


FIGURE 6.3.12 - SELECTED TEST CASE 5 - BUTTOCKS

7.0 TEST CASE COMPARISON

7.1 GENERAL

For each of the five test cases, the following data was provided to and used by each participating CAL developer in Phase II of the project

1. Offsets for sections, waterlines and buttocks in way of each plate.
2. IGES format hi-cubic B-spline surface patches in way of each plate.
3. Definition of seams and marking curves.
4. Body, profile and plan views for each plate labeled for seams, butts and marking curves.

Each CAL participant transfered, and converted where necessary, this data into information useable by their system. They then developed each of the five test cases and delivered 1:10 scale drawings of the developed plates along with tabular data, including coordinates of the developed plate corners, as a means for quick comparison of the different system developments. 1:10 scale partial lines were also provided as a means to check for “causes” of any significant differences between different system developments.

AU of the CAL participants provided more information than required for this study. The presentations by Senermar and Albacore Research Ltd., were impressive in there neatness and ease of understanding.

All of the CAL participants pointed out that test cases 1,2 and 5 did not reflect how such plates would be approached in actual practice. They all stated that they would have divided theses test plates into smaller plates. In fact, the SPADES system would not develop “acceptable” plates, by their normal criteria, for these test cases.

Table 7.1.1 records the comer coordinates for the developed plates for the test cases. There is no way, nor was it the intent to try, to say that one CAL system is the best development The purpose of the table and any comparison is to quickly see if all the systems gave consistent results. It can be seen from the table that this is not the case. Some of the differences are much larger than expected. In the following discussion of each test case, any observed cause of the differences and possible corrective action to avoid the inconsistency is described.

TABLE 7.1.I - COMPARISON OF DEVELOPED PLATE CORNER COORDINATES

	BOTTOM LEFT	TOP LEFT	TOP RIGHT	BTM RIGHT	BTM CENTER
TEST CASE 1					
BMT	0/0	0/3406	5196/3526	6469/0	
FORAN	0/0	17/3405	5222/3507	6469/0	
KCS	0/0	7/3389	5202/3587	6488/0	
AUTOSHIP	0/0	0/3400	5200/3510	6430/0	
SHIPCAM	0/0	16/3406	5203/3501	6442/0	
SPADES	0/0	10/3405	5161/3541	6450/0	
TEST CASE 2					
BMT	0/0	818/1019	7912/949	5753/-2198	2159/-226
FORAN	0/0	797/1016	7890/946	5741/-2195	NO COORDS GIV
KCS	0/0	825/1013	7532/1100	5643/-2268	2079/-226
AUTOSHIP	0/0	870/1090	7880/1000	5740/-2130	2200/-213
SHIPCAM	0/0	881/1024	7889/992	5700/-2132	2159/-220
SPADES	0/0				
TEST CASE 3					
BMT	0/0	41/1874	8555/2163	8408/0	
FORAN	0/0	47/1865	8587/2178	8401/0	
KCS	0/0	26/1871	8548/2165	8408/0	
AUTOSHIP	0/0	0/1860	8530/2080	8410/0	
SHIPCAM	0/0	6/1871	8519/2166	8409/0	
SPADES	0/0	29/1871	8538/1991	8407/0	
TEST CASE 4					
AUTOSHIP	0/0	9/3320	5730/1320	5610/0	
SPADES	0/0	158/3392	5761/1094	5609/0	
TEST CASE 4U					
BMT	0/0	-90/1720	5649/253	5703/0	
FORAN	0/0	-85/1743	5718/245	5710/0	
KCS	0/0	-79/1741	5713/257	5693/0	
TEST CASE 4L					
BMT	0/0	0/1593	5699/1091	5611/0	
FORAN	0/0	0/1590	5708/1072	5611/0	
KCS	0/0	0/1592	5679/1082	5609/0	
SHIPCAM	0/0	6/1588	5696/1076	5604/0	
TEST CASE 5					
BMT	0/0	188/3528	15111/2602	16481/0	
FORAN	0/0	35/3503	15293/2752	16259/0	
KCS	0/0	567/3492	14561/2512	16171/0	
AUTOSHIP	0/0	354/3310	15112/2731	16259/0	
SHIPCAM	0/0	98/3518	14968/2861	16109/0	
SPADES	0/0	253/3441	15541/2566	15441/0	

7.2 CASE 1- UPPER BULBOUS BOW PLATE

Figures 7.2.1 through 4 show the typical summary sheets provided by AUTOKON, BMT, FORAN and ShipCAM. The developed plate corner coordinate differences for this plate are up to 86 mm in the length and 58 mm in the width. An examination of each 1:10 developed plate drawing and the corresponding partial lines showed no anomalies that could have caused the differences. Some of the CAL participants expressed concern as to the location of the forward button the center line of the ship at the stem. They suggested that the forward butt should be located aft of the extent of the stem radii tangency line. The SPADES test case actually inserted such a butt running parallel to and aft of the stem line at a distance of 200 mm. The forward comer coordinates for the SPADES test data were corrected to account for this in the table to enable them to be used in the comparison.

Figure 7.2.5 shows the extent of the differences in the outlines of the developed plates for the different CAL systems.

7.3 CASE 2- APERTURE TOP PLATE

The developed plate comer coordinate differences are quite significant ranging from 77 mm to 380 mm. The difference in shape was quite noticeable, as can be seen from Figure 7.3.1, which shows the outlines of all developed plates. Again the cause is probably-due to the amount of data used to define the ship hull surface in the region.

The test plate is probably the second most difficult of all the test cases, having reverse double curvature and twist Considering this all the developments are remarkably close with the exception of the AUTOKON development

In actual practice this plate would be split into a number of plates to make it easier to develop and form. Also stock would be provided on the two lower edges and aft butt

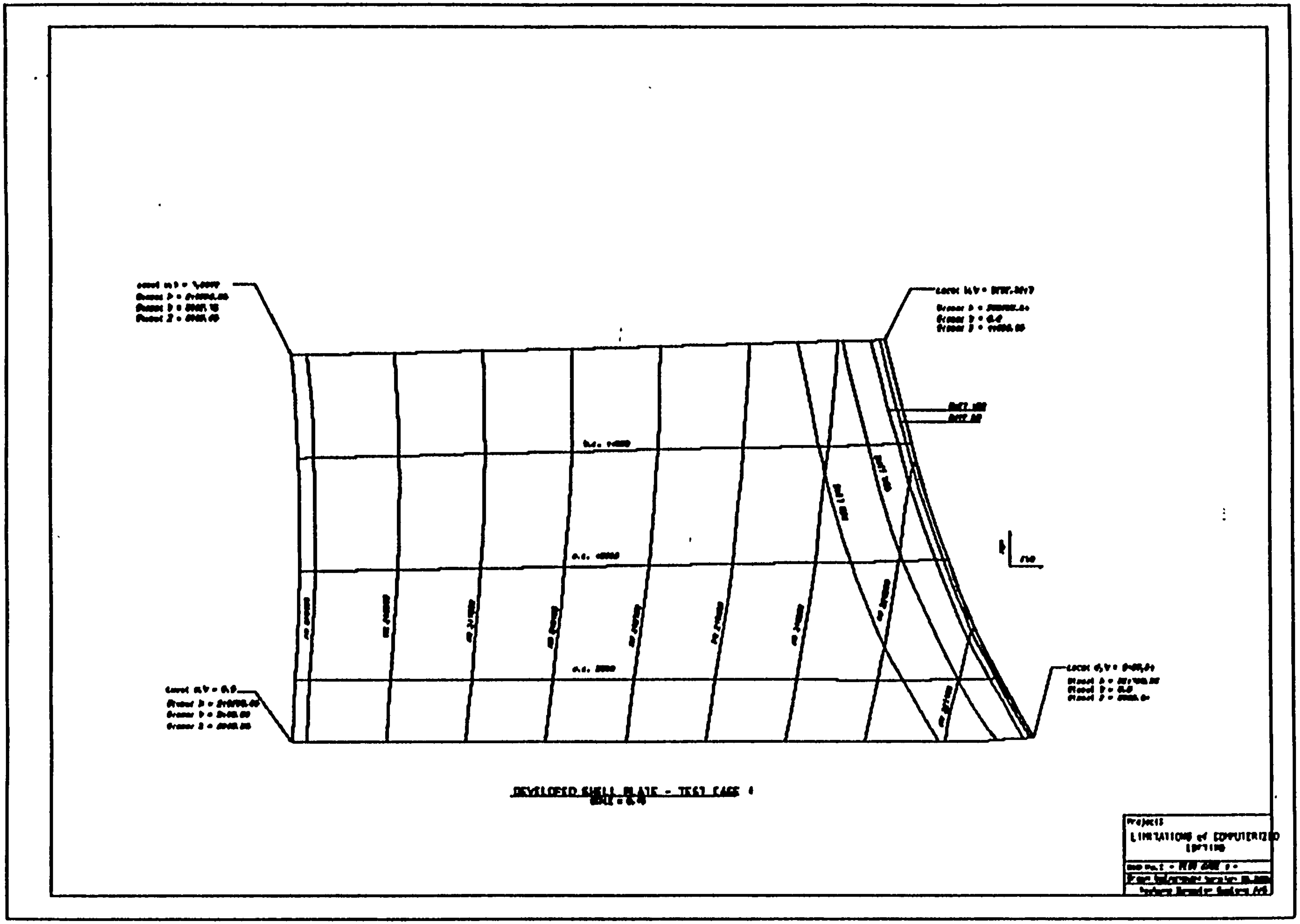


FIGURE 7.2.1 - TYPICAL PLATE DEVELOPMENT SUMMARY FROM AUTOKON

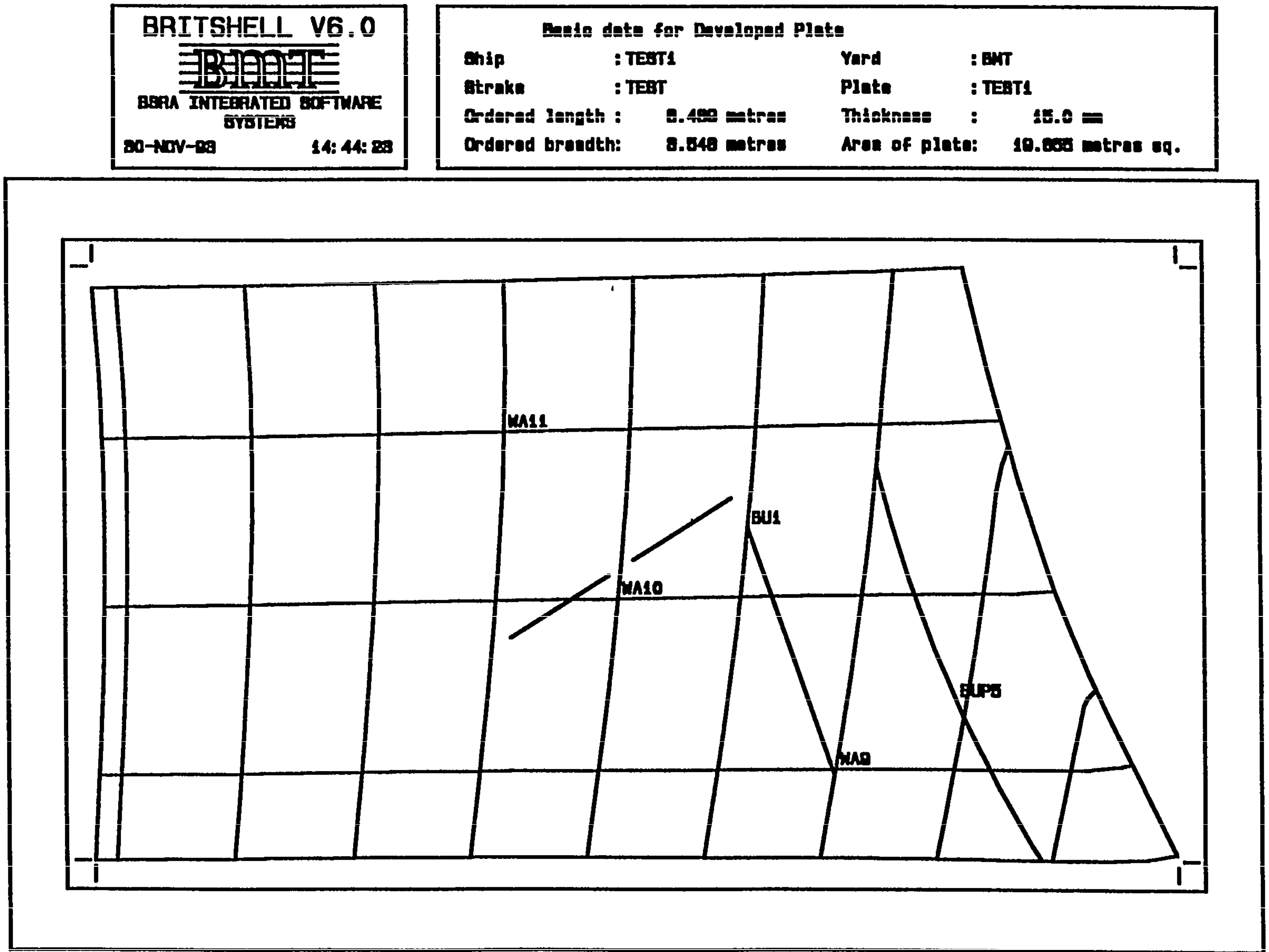


FIGURE 7.2.2 - TYPICAL PLATE DEVELOPMENT SUMMARY FROM BMT

FORAN SYSTEM - MODULE UT06 VERSION 20 RESULTS PAGE 001

DATE - 93.06.15

CUSTOMER - T. LAMB

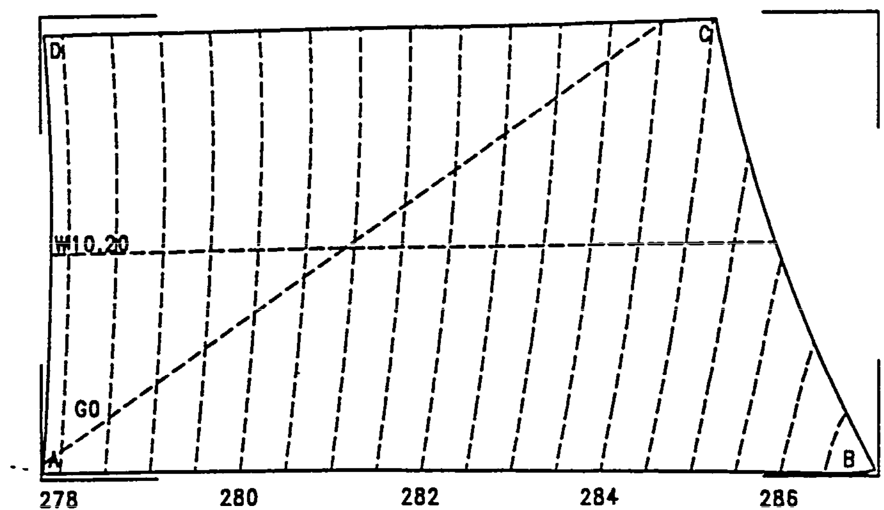
:SCRIPTION OF SHIP - TEST 1+2

PROJEC	CONSTR	FNAM
TEST12	TEST12	LAMB

BLOCK - TES1 PANEL - 001 PART - 1

DESCRIPTION - TEST PLATE 1

FNAM=LAMB DECK= 00 SCALE=1/51
BLK = TES1 PAN = 001 PART = 1



STEEL ORDER

PLATES TO BE MADE 1 OF QUALITY A
DIMENSIONS GROSS PLATE 6500 * 3600 * 15.0 MM.
GROSS WT. 1 * 2755 KGS. NET WT. 1 * 2318 KGS. SCRAP 15.9 0/0
THE REPRESENTED PLATE IS OF PORTSIDE

CUTTING

LENGTHS OF THE EDGES : AD = 3407 AB = 6462 BC = 3728 DC = 5206 MM
CURVES EDGES: IDENTIFICATION AD AB BC DC LENGTH 18804 MM
PROCESS OF CUTTING RECOMENDED M/MA
LENGTH OF THE DIAGONALS OF DEVELOPED PLATE D.AC= 6288, D.BD= 7286 MM

BENDING

NUMBER OF PARTS TO BEND 1
WARPING INDEX 5
MINIMUM LENGTH OF CYLINDER OR PRESS 6286 MM
BENDING PROCESS : DOUBLE CURVATURE

NOTES.-M/MA : MANUAL OR AUTOMATIC CUTTING MACHINE.
-MP : PARALLEL EDGES CUTTING MACHINE.

FIGURE 7.2.3 - TYPICAL PLATE DEVELOPMENT SUMMARY FROM FORAN

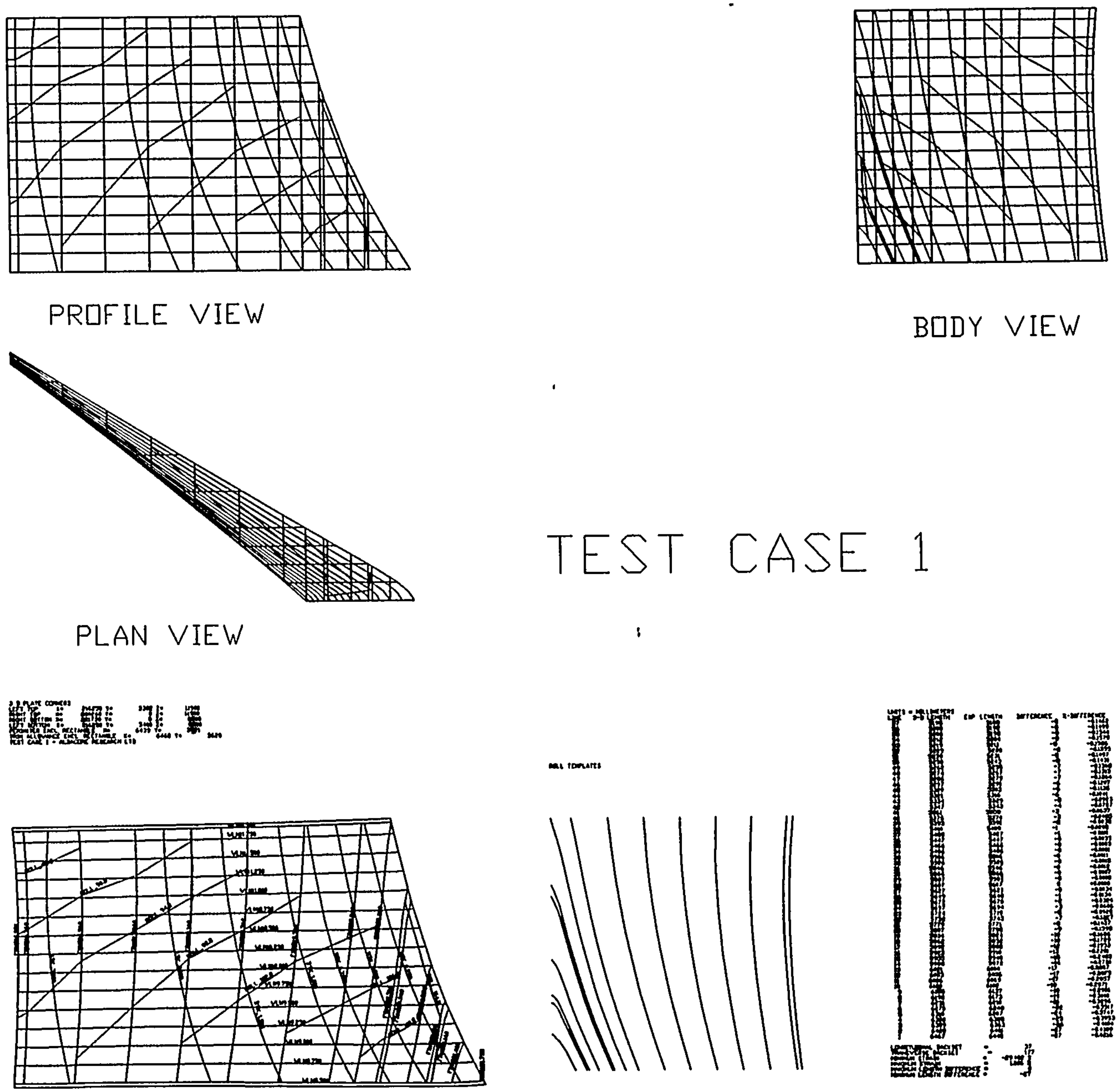


FIGURE 7.2.4 - TYPICAL PLATE DEVELOPMENT SUMMARY SHEET FROM SHIPCAM

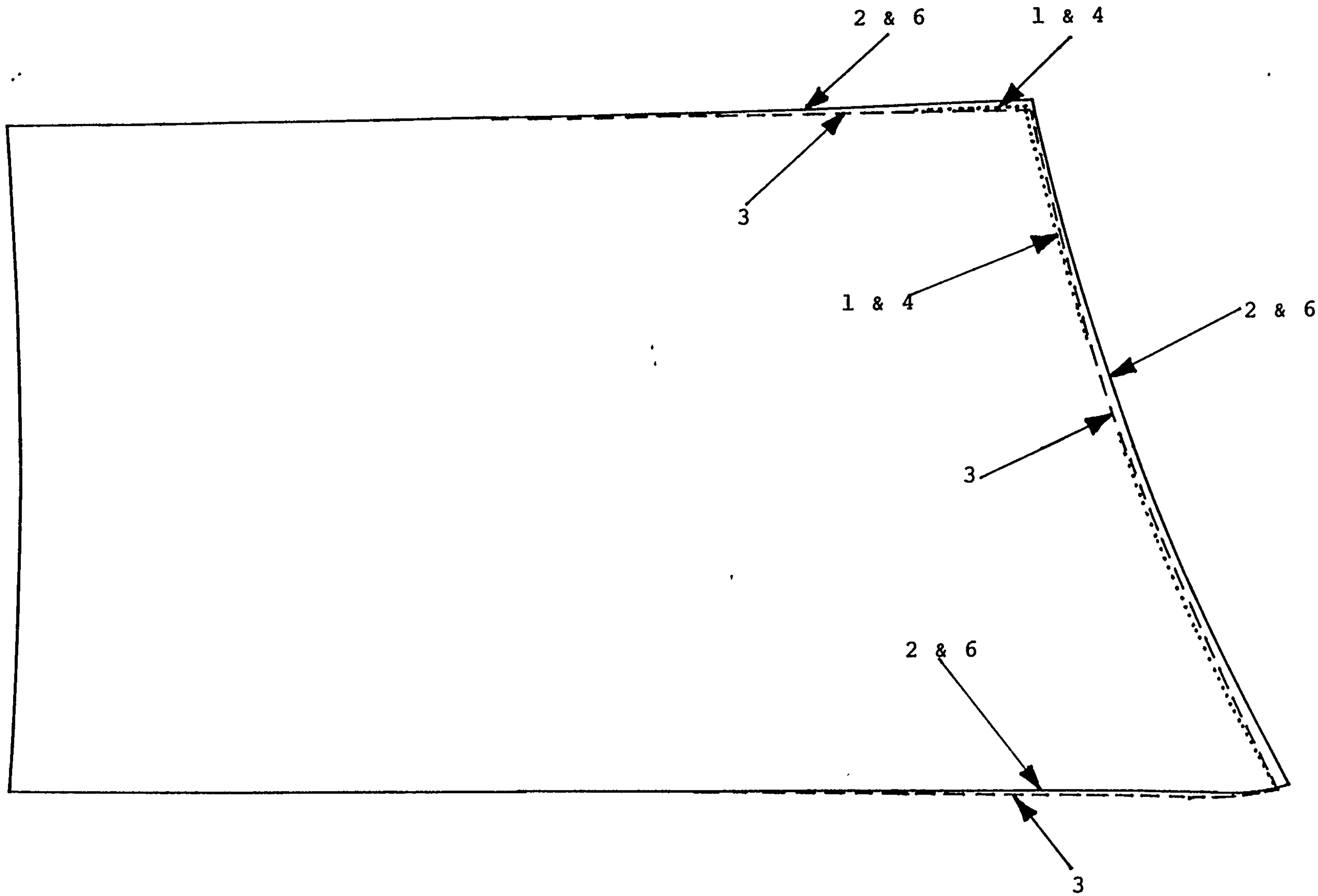


FIGURE 7.2.5 - TEST CASE 1 DEVELOPED PLATE OUTLINES

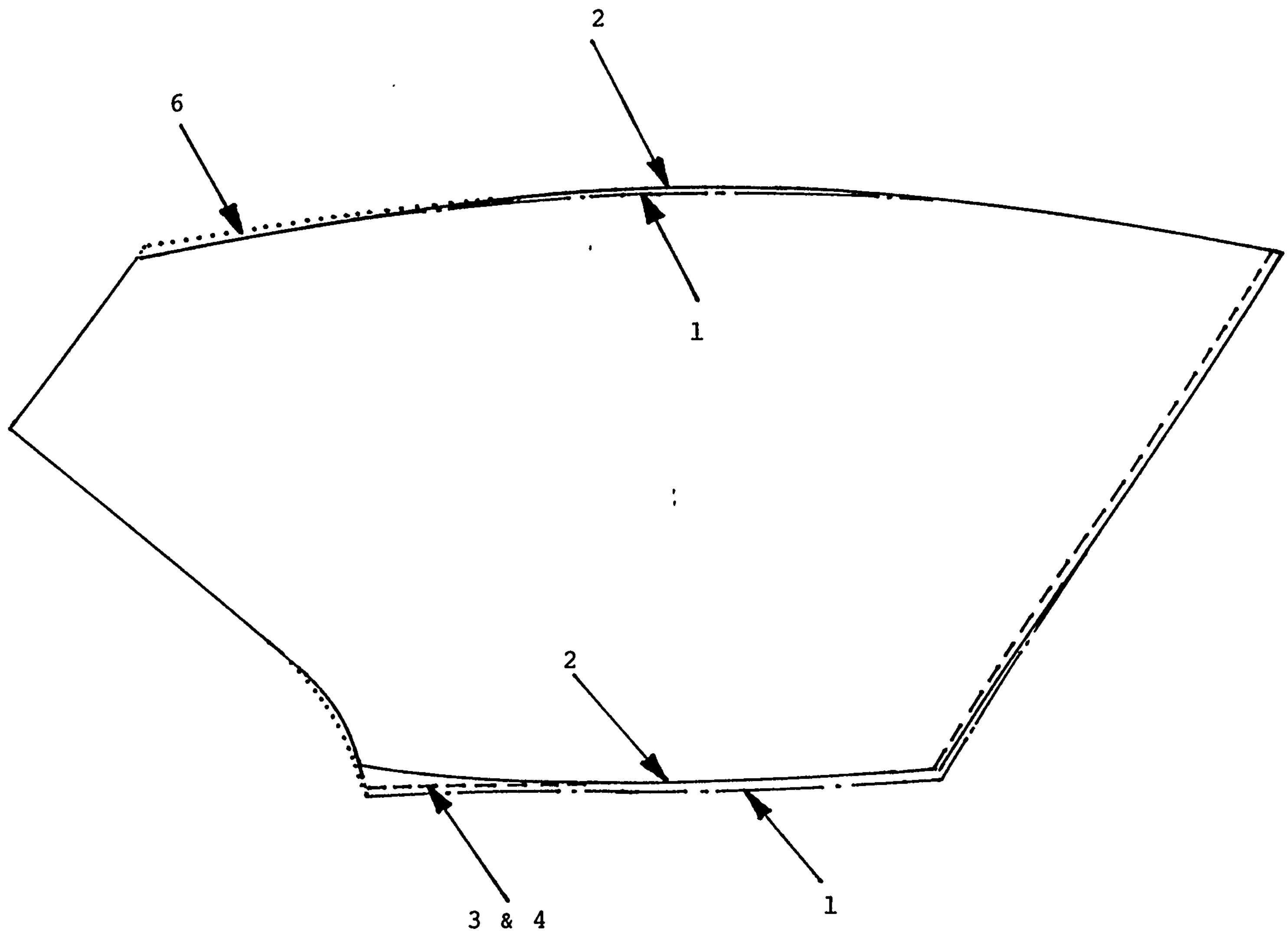


FIGURE 7.3.1 - TEST CASE 2 DEVELOPED PLATE OUTLINES

7.4 CASE 3- FORWARD SHOULDER PLATE

The developed plate comer coordinate differences are quite large, especially in the width. This plate, although it appears simple, has been reported to be a problem for many shipbuilders. The “hidden” problem is that its surface crosses the bottom tangency line, going from a flat surface to double curvature. This problem resulted in the forward comers having differences up to 66 mm in the length direction and 177 mm in the width direction.

Figure 7.4.1 again shows the extent of the differences in the developed plates by superimposing the outlines for the different CAL systems.

In this case these differences are entirely due to the development methods in that the surface was adequately defined by the data.

To reduce the impact of this problem, such plates should have a butt located as close as possible to the tangency line on the flat portion.

7.5 CASE 4- HORIZONTAL TOP SEAM PLATE

This plate was split into an upper and lower plate by AUTOKON, BMT FORAN and ShipCAM, though ShipCAM only developed the lower plate. AutoShip and SPADES developed both plates as one. It is the upper plate that is of interest as it incorporates the horizontal top seam.

The developed plate comer coordinate differences are again larger, by up to 36 mm, in the length direction and less, up to 23 mm, in the width direction.

The superimposed developed plate outlines are shown in Figure 7.5.1.

The surface of this plate was again completely defined and should not be the cause of the differences.

This type of plate cannot be avoided as it is the result of using structural blocks with horizontal seams in the shaped hull areas. Therefore stock appears to be the onIy acceptable solution. From the differences it would appear that 50 mm of stock would be adequate. However, this would not account for any differences due to forming accuracy.

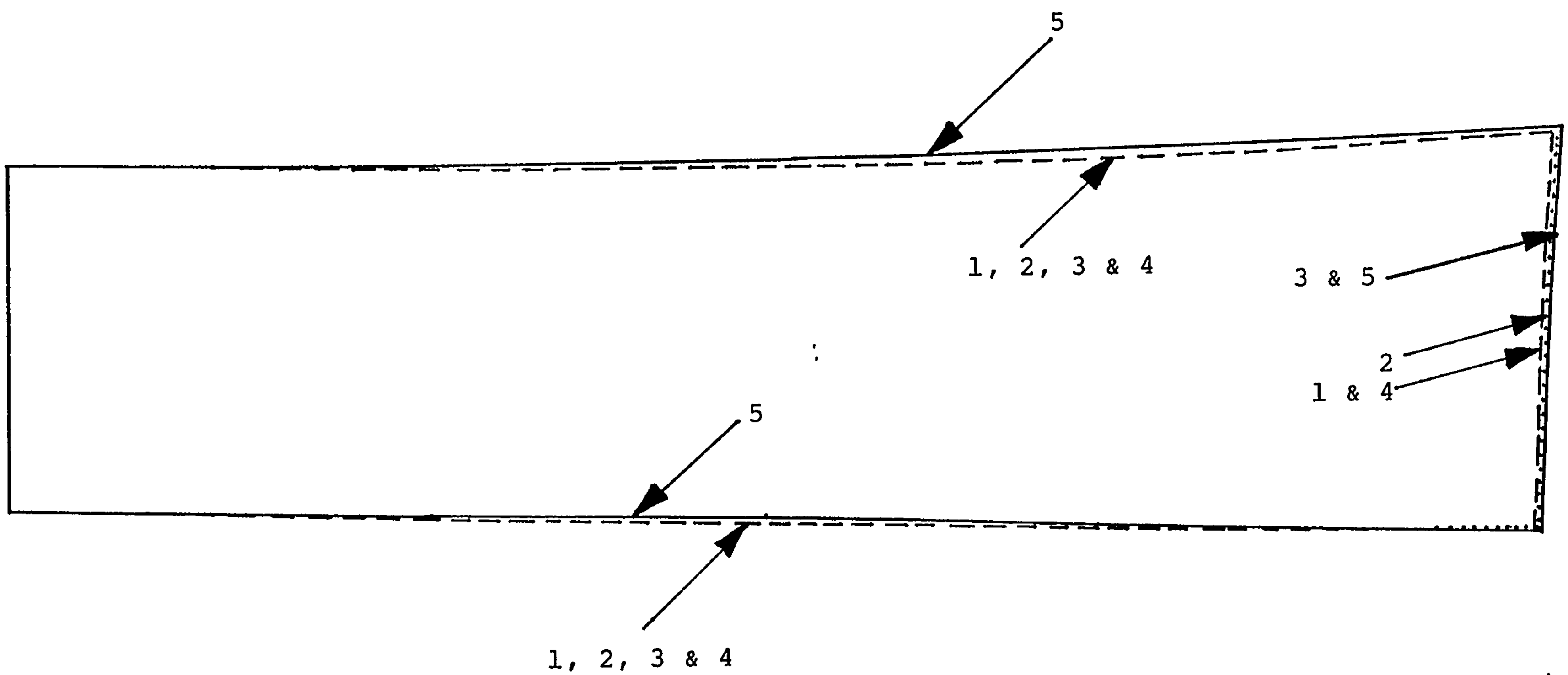


FIGURE 7.4.1 - TEST CASE 3 DEVELOPED PLATE OUTLINES

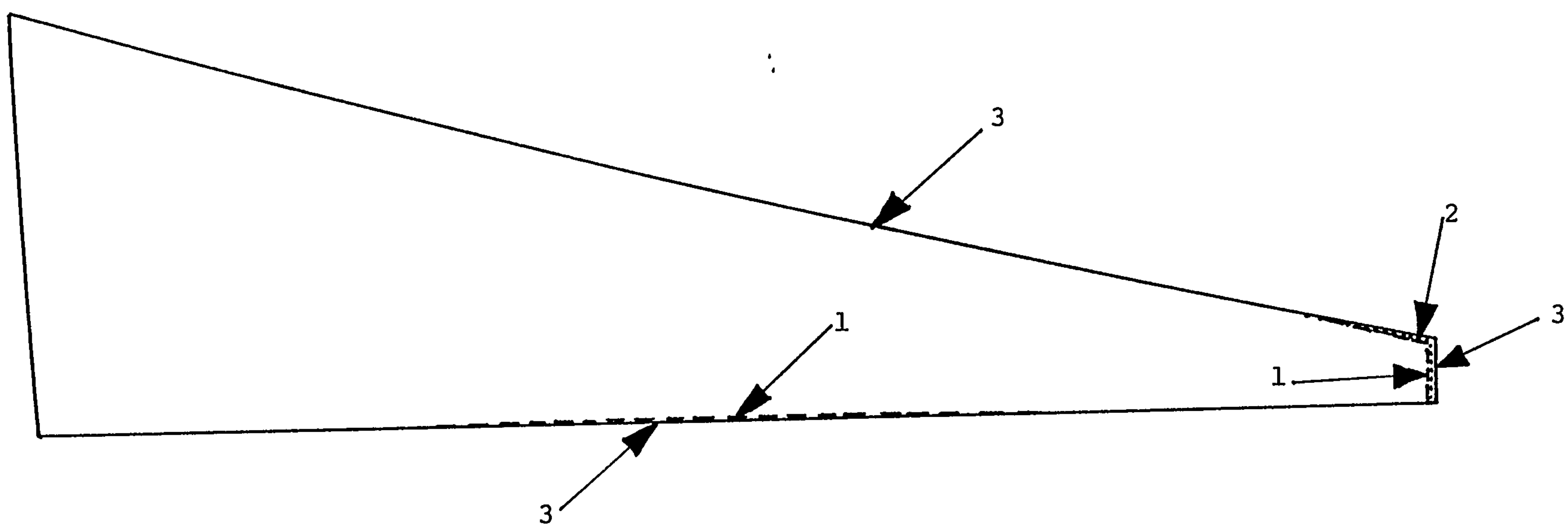


FIGURE 7.5.1 - TEST CASE 4 DEVELOPED PLATE OUTLINES

7.6 CASE 5- SONAR DOME PLATE

This test plate is the most complex of alI the cases plus it was very large. In actual practice it would have been divided into at least four smaller plates by one additional seam and butt However, it is a good example of how not to define complex shell plates.

The differences between the developed plate shapes is quite significant as can be seen from Figure 7.6.1, which superimposes the developed plate outlines for all six participants

The magnitude of the difference in the developed plate comer coordinates is up to 1282 mm in the length direction and 937 mm in the width direction. The reason for this is mainly due to the CAL systems inability to handle such a complex shape. Also the inadequate surface definition again is a probable factor. However, by dividing the plate up into a number of smaller plates would improve both the development acceptability as well as the consistency between the different developments.

7.7 CASE SUMMARY

The results of the test case comparison suggests that acceptable consistency, such as differences less than 10 mm, between the different CAL systems for double curvature shell-plates is not attainable. Even in the less complex test plates of Cases 3 and 4 the differences are too large.

This lack of consistency highlights and substantiates the already stated fact that it is mathematically impossible to develop an exact flat pattern for a plate with double curvature. However, the size of the differences between CAL systems is surprising and of concern. It is impossible to determine if any system is more acurate than another, nor was it the intent of this study to attempt to do so. However, the lack of consistency would tend to substantiate the shipbuilders position that there is still problems with the system accuracy, rather than the CAL developers position that the problems are mainly due to the forming methods, tools and worker skill levels.

It is recognized that it is not the consistency between different CAL systems that is of major interest to shipbuilders using the systems, but rather the accuracy of fit up from plate to plate developed by the same CAL system. This study did not address this aspect in the test cases.

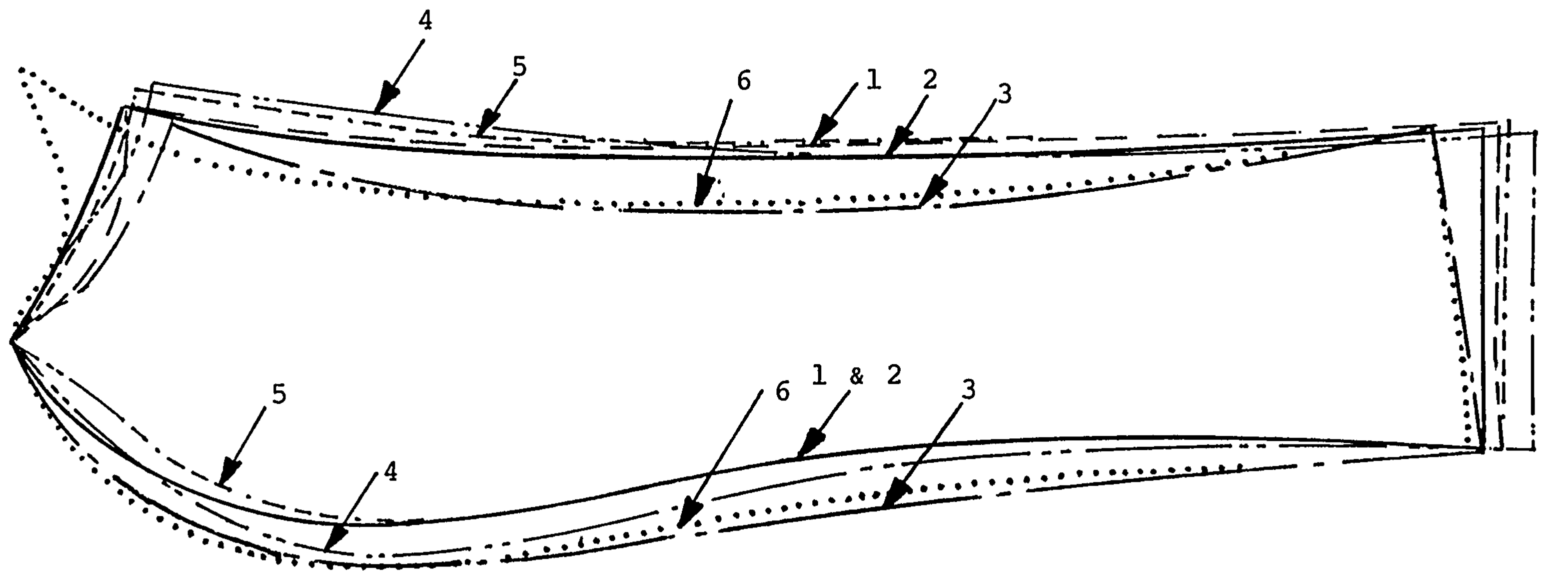


FIGURE 7.6.1 - TEST CASE 5 DEVELOPED PLATE OUTLINE

8.0 STUDY CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

A The shell development problems are viewed differently by shipbuilders and the CAL developers. This is surprising when it is remembered that computer aided lofting shell development methods have been in use for over 20 years. It would seem reasonable to expect developers and users (shipbuilders) to have worked together on the problems, or at least be in agreement as to what they are.

B. A review of papers by foreign shipbuilders covering computer aided shell development did not show the same concerns as some of the U.S. shipbuilders. Their message is that successful shell plate forming and erection is as much or more dependent on the material handling and forming equipment, and the skills and training of the forming and erection workers as it is on the computer aided lofting method capability.

C. While improvements have been made to all of the CAL developers' shell development systems over the years of use, they have been in the user interface and to take advantage of computer improvements. None of the traditional CAL developers have incorporated major new techniques that significantly added to the accuracy of the developed plate flat shape. FORAN'S use of geometric surfaces patched into the flat plate is a different approach, as is the ShipCAM and AutoShip use of a finite element technique, but again it is not known if they improve on the triangulation accuracy.

D. The CAL systems are not "expert systems" nor do they incorporate "artificial intelligence". This means that the use of the system, and specifically shell development, will be highly dependent not only on the experience the user has with the system but more importantly the user's skill level and experience as a shipbuilding loftsman.

E. For most of the compound curvature shell plates on a ship's hull, the accuracy of the shell development systems is well within normal shipbuilding tolerances.

F. The shipbuilders' bn goal, to cut all shell plates neat, probably will not be realized in the foreseeable future. This is due to two facts, namely

1. It is mathematically impossible to develop an exact flat pattern for any plate with compound curvature.
2. Shipbuilding plate forming tools and operator skills do not have the required consistent and repeatable accuracy.

G. The development of the same plate by different CAL systems is not consistent even for the simpler test plates. The differences get significantly worse as the plate complexity increases. However, the consistency can be improved by dividing the complex shell plates into a number of smaller plates.

H. It is recognized that it is not the inconsistency between different CAL systems that is of importance to the shipbuilders who use the systems, even though it supports their concern as to the acceptability of current systems. They are more interested in the good fit up from adjacent plate to plate developed by the same CAL system, after cutting and forming. This study did not address this matter. To do so would have required groups of plates in each test area to be developed and then to have actually cut, formed and connected the plates. This was not within the scope of the study.

8.2 RECOMMENDATIONS

It is recommended that

A. A study be undertaken of shipbuilding forming methods and the application of accuracy control to improve shell plate forming accuracy and consistency.

B. A study be undertaken to develop ways to use advanced measuring devices, such as laser theodilites, for the checking and control of shaped shell plate forming.

C. Shipbuilders and CAL developers work together to develop new and improved computer developed data to assist shell plate forming operators to attain better accuracy and consistency

D. A study be undertaken to physically match a number of adjacent shell plates on an actual block for plates developed by a number of the CAL developers involved in this project, to determine fit up accuracy or lack thereof, as discussed in 8.1 H above. This would obviously have to be performed by a shipbuilder with the capability to cut and form the shell plates involved and to assembly them on a jig. The shipbuilder must have the capability to accurately measure the cutting, forming and fit up of the shell plates before joining as well as the overall final panel accuracy after joining the individual shell plates. The block selected should have at least the shape complexity of Cases 3 and 4.

9.0 **REFERENCES**

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10.0 APPENDICES

10.1 CAL Developers' Reports

10.1.1 Albacore Research Ltd
10.1.2 BMT ICONS Limited
10.1.3 Cali &Associates, Inc
10.1.4 Coastdesign Inc
10.1.5 Kockums Computer Systems AB
10.1.6 Senermar

10.2 Boeing Commercial Airplane Group Letter

10.3 Key Line Marking Method For Curved Shell Panels

APPENDIX 10.1.1

ALBACORE RESEARCH LTD. REPORT

Shell Development Limitation Project

Part A, Band C

by

Albacore Research Ltd.
3080 Uplands Road
Victoria, B.C.
Canada
V8N 1 N2

Rolf G. Oetter

A. DESCRIPTION OF SHELL DEVELOPMENT METHOD

1. Introduction

ShipCAM3 is an integrated shipbuilders software package which includes tools for computerized fairing, lofting, developable surface expansion and shell expansion. It has been specifically developed for the small and medium sized shipyards, but also large shipyards may find it usefuL It runs on IBM PC compatible computers, which makes it very affordable. ShipCAM3 closely integrates with off-the-shelf CAD programs, such as AutoCAD. ShipCAM3 passes the geometric data such as faired lines, frames and expanded shell plating to CAD systems for detailing.

ShipCAM3 has been marketed for two years. The shell expansion module has been used for about one year. A few ships have been built to date using the shell expansion, and the results are very good.

The SHELL EXPANSION module is based on triangulation of a surface mesh. The surface mesh may be created by ShipCAM3 itself or imported from other programs, including ship design programs, such as FASTSHIP/YACHT or AutoShip.

The SHELL EXPANSION program has a fully integrated graphical user interface. The result of a performed shell expansion is immediately displayed on the semen for visual inspection. A typical expansion take less than a second to compute. The expanded plate is displayed in mesh form including all marking for frame lines, water lines and buttock lines. Next the 'strain map' of the plate may be displayed. A strain map and the total longitudinal stretching aid the operator to decide about the quality of the plate expansions.

All plate geometry information, including the strain map may be exported to the CAD systems for detailing and nesting.

2. DETAILS OF PROCEDURES USED

2.1 Data Preparation

The ShipCAM3 computer aided ship manufacturing system consists of a number of self contained modules. These modules exchange data through geometry data files. ShipCAM3 provides a number of ways to import the geometrical data at different stages into the program

The shell expansion modules requires a surface mesh which approximates the hull surface. The mesh vertices are connected by straight lines in 3-d space. Here are in brief some common ways to import the required data.

- The traditional way to is to enter the table of offsets into the system and fair the lines in transverse (stations) and longitudinal directions. The faired lines are then converted into the above mentioned surface mesh using a 4th-order B-spline surface algorithm.

- Another possibility includes the dixect import of the hull form from hull design programs, such as FAST-SHIP/FAST YACHT and AutoShip.

- Line plans from CAD programs can be imported as easily. The IMPROT module allows for a multitude of manipulations in order to convert the hull geometry description to the required format.

The such acquired hull geometry may stretch over the complete hull or cover only a small part such as an appendage or a repair area.

The number of the mesh vertices required for a successful shell expansion depends on the complexity of the shape to be expanded. The more vertices the better the approximation of the actual shape. Typically one vertex should be on each mesh line of the plate for each three degrees of change in direction.

2.2 Shell Expansion Procedure

2.2.1 Loading the 3-D geometry file

The operator loads the geometry file with the 3-D hull geometry into the computer memory by simply selecting the file name from a presented list The surface-mesh is displayed on the screen and may be viewed in any of the three principal planes.

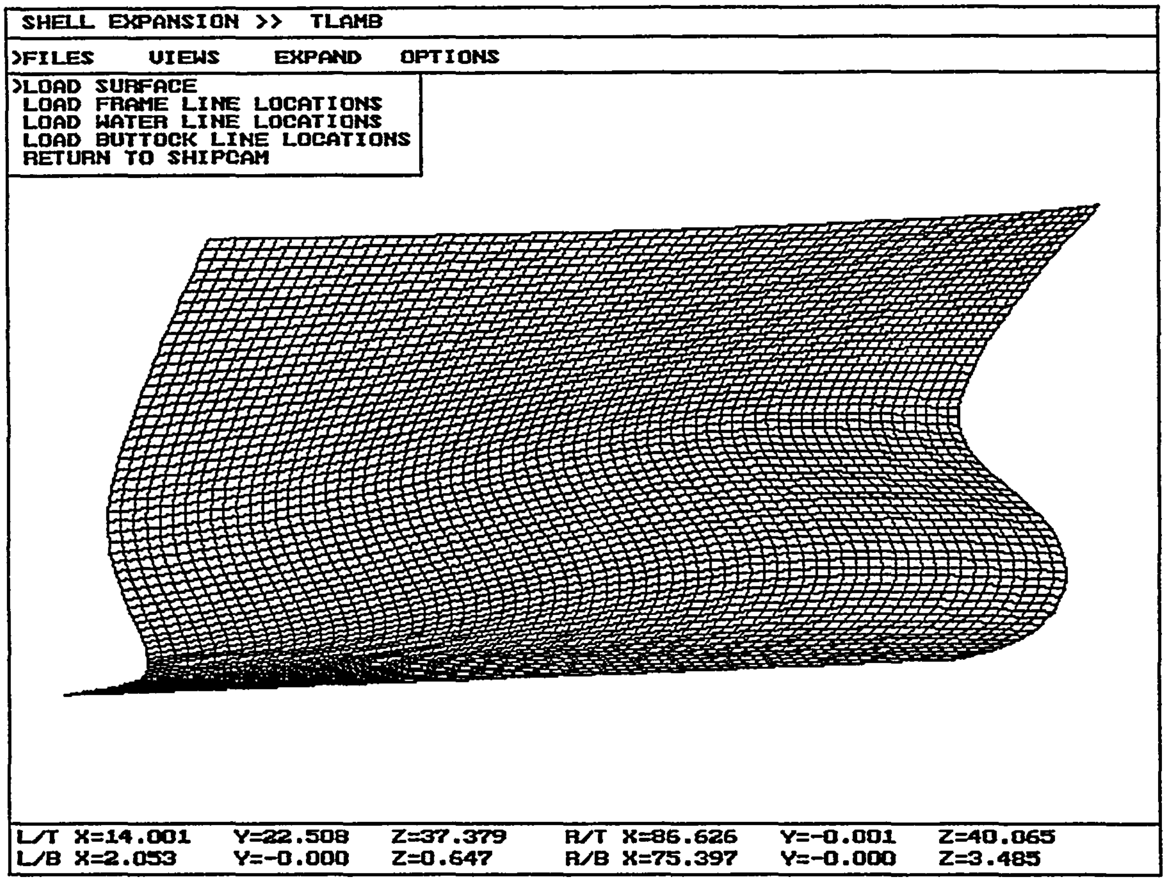


Figure 1: Surface mesh loaded for shell expansion

2.22 Loading the marking location files

Next the operator may load and edit three marking location files which list information about the markings to compute on the expanded plate. Markings can be provided for planes parallel to the three principal views, that is parallel to the water plane, the center plane and the body plane. The resulting markings on the plates are therefore on or parallel to water lines, buttock lines or frame lies.

2.2.3 Selecting the plate to expand

The surface can be expanded as one large plate or as several smaller plates. The break down into several parts is done interactively on the screen by selecting any of the transverse or longitudinal mesh lines as boundaries. The plate is bounded by a left, top, right and bottom border, each of which is a mesh line. The longitudinalsor transverse mesh lines may culminate in one point. The use of mesh lines for plate boundaries may seem to be limiting at first. However, ShipCAM3 exports the expanded plates with all markings to the CAD program. Other plate edges can then be obtained in the CAD program by trimming the plate within the CAD system to any of the marking lines.

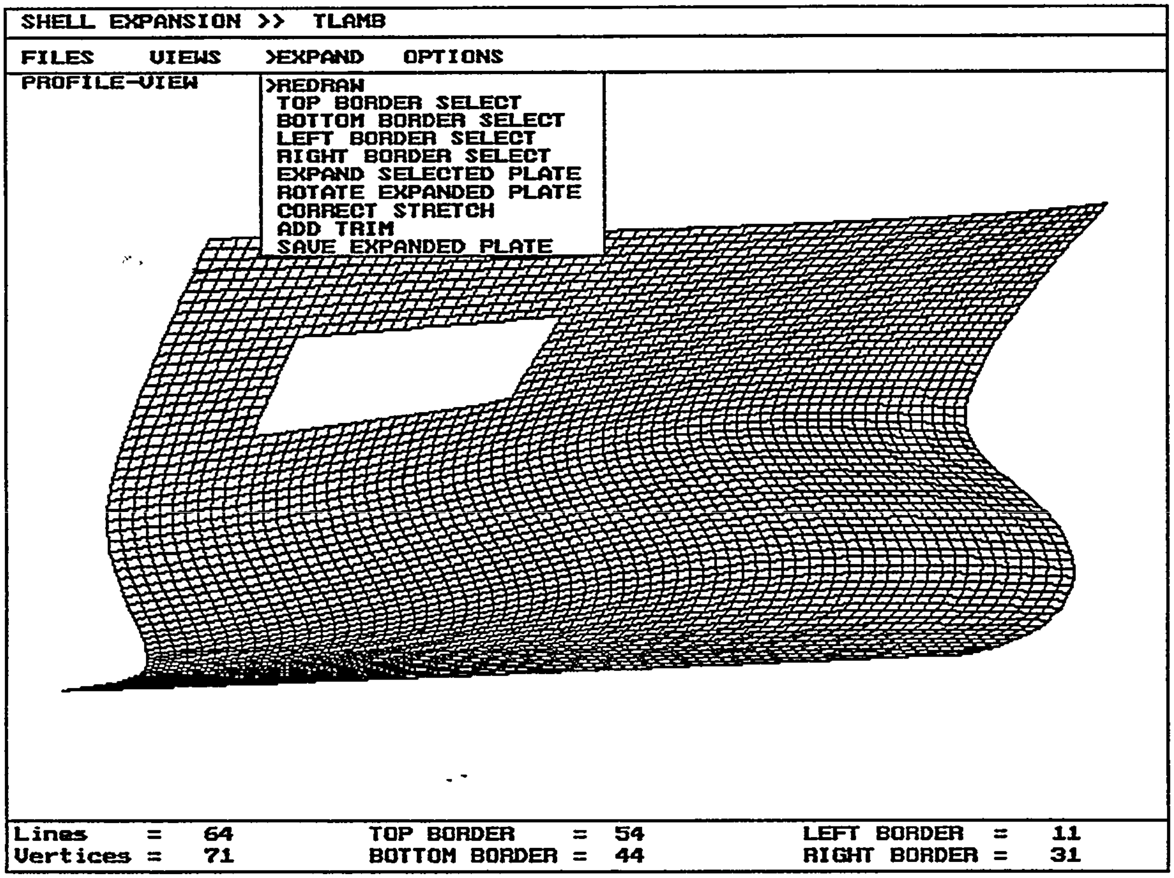


Figure 2: Mesh surface with selected plate to expand

2.2.4 Expanded plate geometry

The result of the shell expansion are four 2-D geometries which are:

- the expanded surface mesh
- the markings parallel to the water line plane
- the markings parallel to the buttock line plane
- the markings parallel to the frame line plane

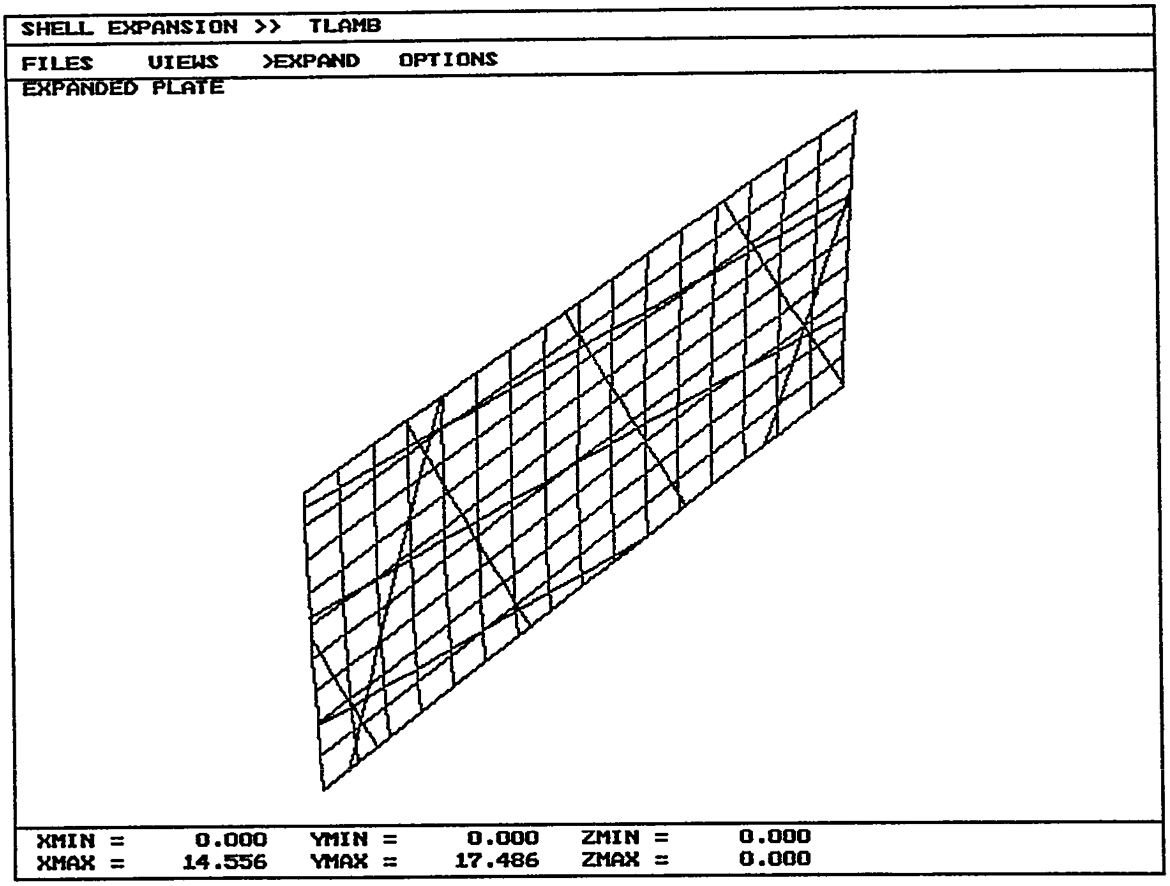


Figure 3: Example of an expanded plate with all markings

2.2.5 Internal strain map

Any 3-D shape containing double curvature will experience deformations when expanded to 2-D flat plate. Comparing the 3-D initial size of a mesh element with the 2-D size of the expanded mesh element enables the strain to be computed. The operator may display the internal strain due to the expansion process. The internal strain is represented by filling each mesh element with a color according to a color strain table. That is, the grade of deformation is represented by a color. Both compression - the 2-D element is smaller than the 3-D one- and stretching-the 2-D element is larger than the 3-done, are displayed.

The deformation strain is a very good indication of the complexity of the 3-D shape, and is used by the operator to decide whether a larger or smaller plate size should be indicated for this area of the hull.

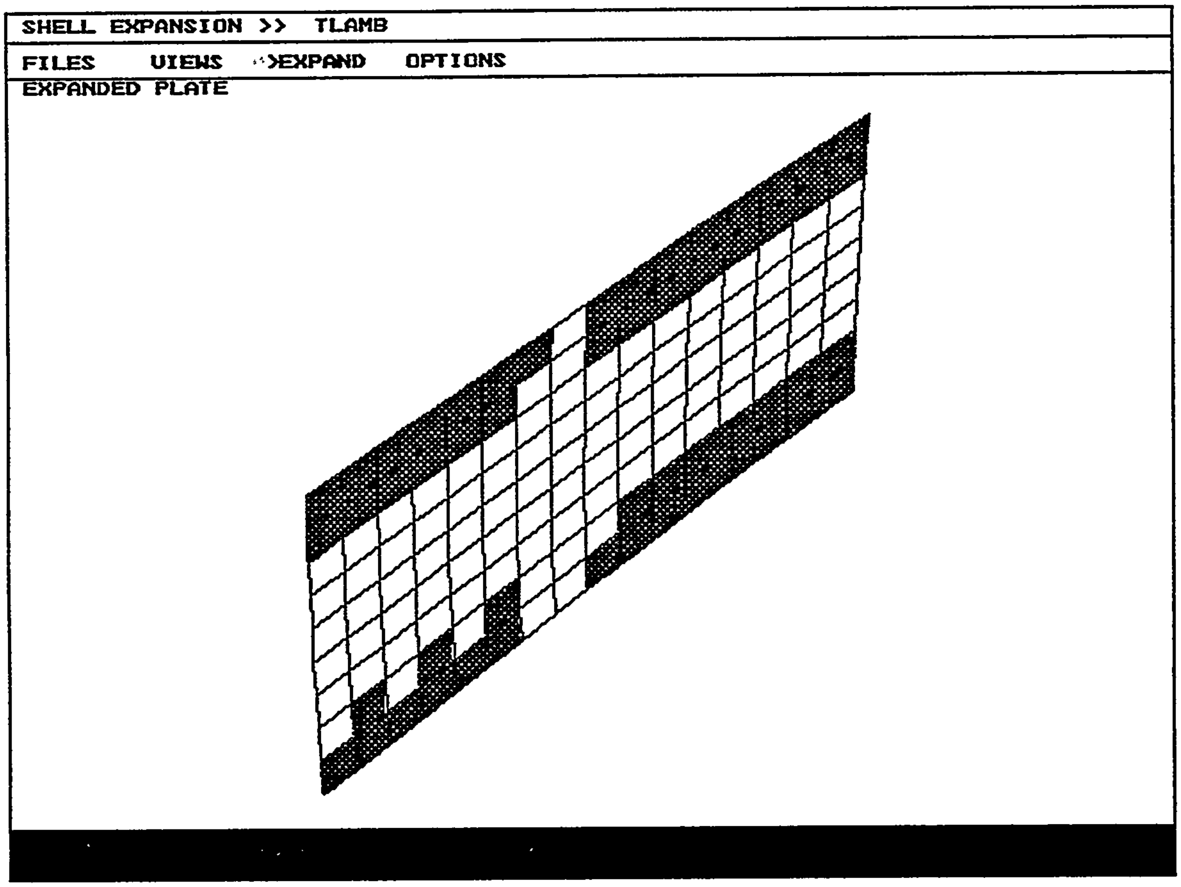


Figure 4: Black and white example of a strain map

The bottom of the screen (black bar in Figure 4) displays the strain values that are represented by a certain color. Unfortunately the blck and white reproduction do not display the details.

2.2.6 Total longitudinal deformation

Lastly the operator may display the total deformation of the longitudinal mesh lines. The implementation of the expansion algorithm, as explained later in this text, allows only for longitudinal deformation of the mesh elements. The transverse lines keep their original lengths. The screen display lists for each longitudinal mesh line

- the 3-D length
- the 2-D length
- the actual change in length
- and the length change in percent of the 3-D length

Positive values indicate the expanded longitudinals are longer than the 3-D longitudinals, negative values indicate that the 2-d longitudinals are shorter.

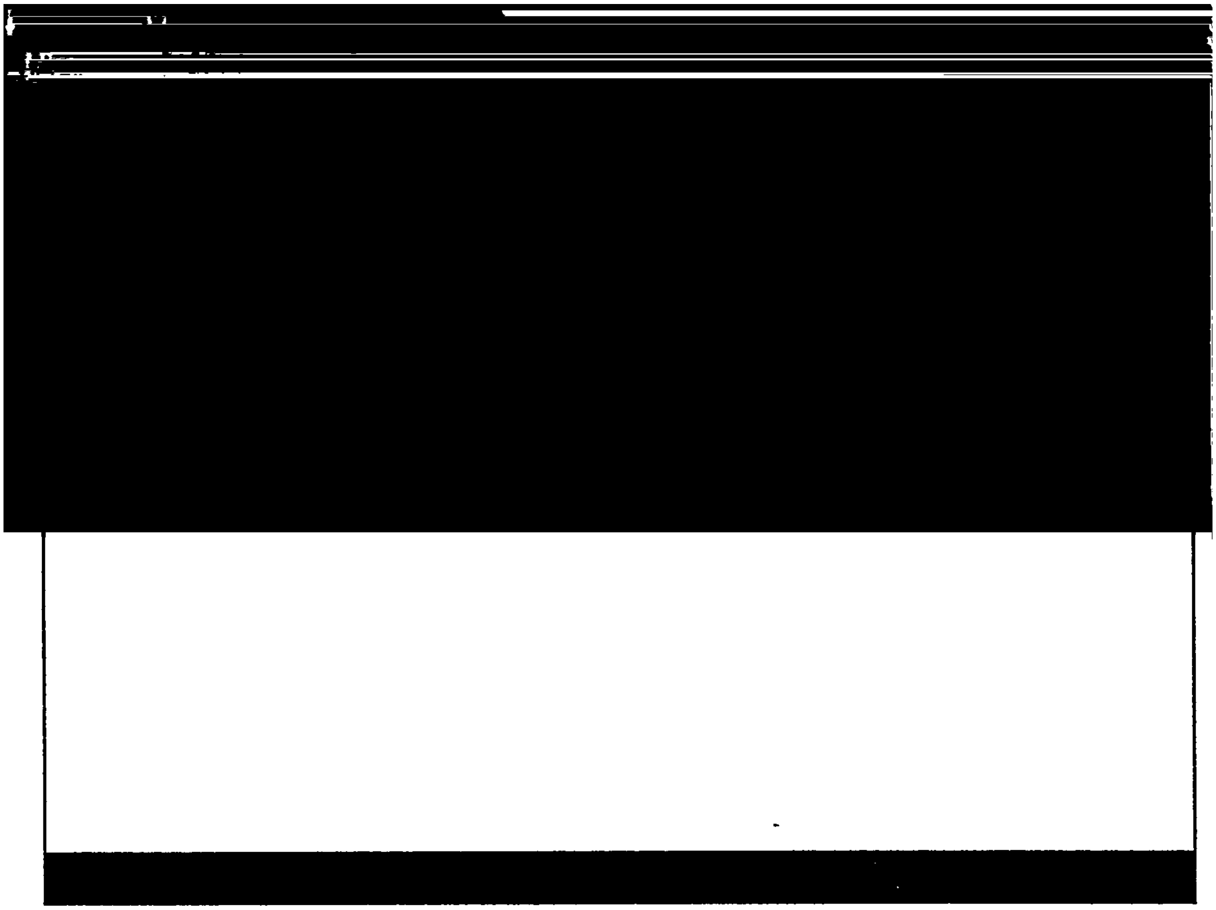


Figure 5: Example longitudinal deformations

The absolute longitudinal deformation may be used to decide whether a smaller plate size should be selected It can also be used to determine the necessary trim allowance to add to the expanded plate.

The example above shows that the longitudinals 5 and 6 have no length differences between the 3-D plate and the 2-D expanded plate. The two longitudinals closest to the center will never show any stretching, since the algorithm starts expanding in the center of the plate and there is no compound curvature. Longitudinal further towards the edge of the plate may be subject to significant length changes. The amount of total stretching or compression depends on the amount of double curvature. In this example the maximum length difference is 0.0166 feet or about 3/16". The length difference of each longitudinal may be devided by two and the resulting value added to each end of the plate as trim.

2.2.8 Compensating the longitudinal deformation

The longitudinal deformation is known for each longitudinal. The stretch may be compensated for by adding one half of the total length difference to the each longitudinal at either end of the plate. This procedure is performed automatically by selecting CORRECT STRETCH from the screen menu.

2.2.9 Adding Trim

Trim may be added in longitudinal direction. To add the trim the operator selects ADD TRIM from the menu. The system asks for the amount of trim for both seams of the plate and then extends the longitudinal by the given amount The hatched area in Figure 6 shows an example of trim added on the left side of a plate.

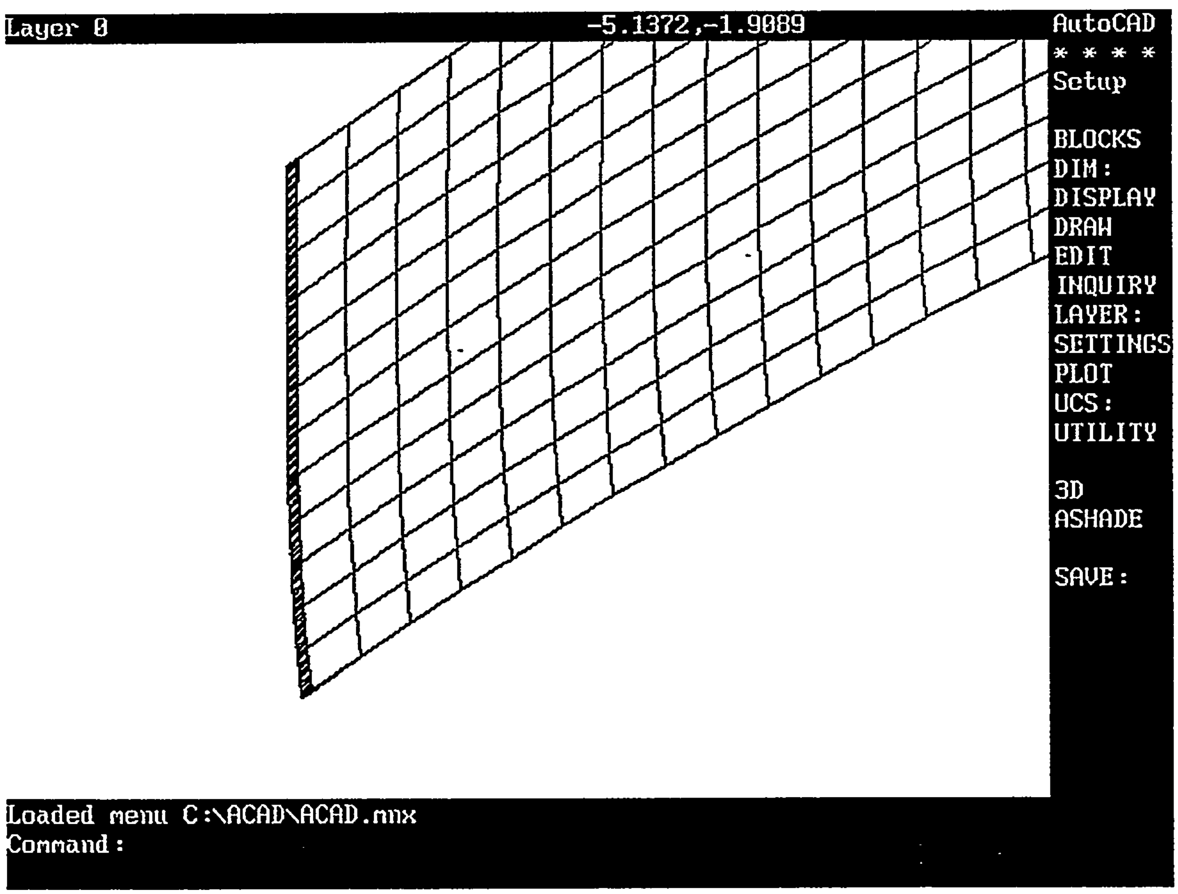


Figure 6: Detail for trim on the left edge of the plate

2.2.10 Plate sizing

The resulting plate may be rotated to fit available stock. The maximum length and width dimension are displayed. The operator checks the plate size against the available stock and decides if another plate size would be more suitable. Another size can be chosen and calculated in less than five seconds.

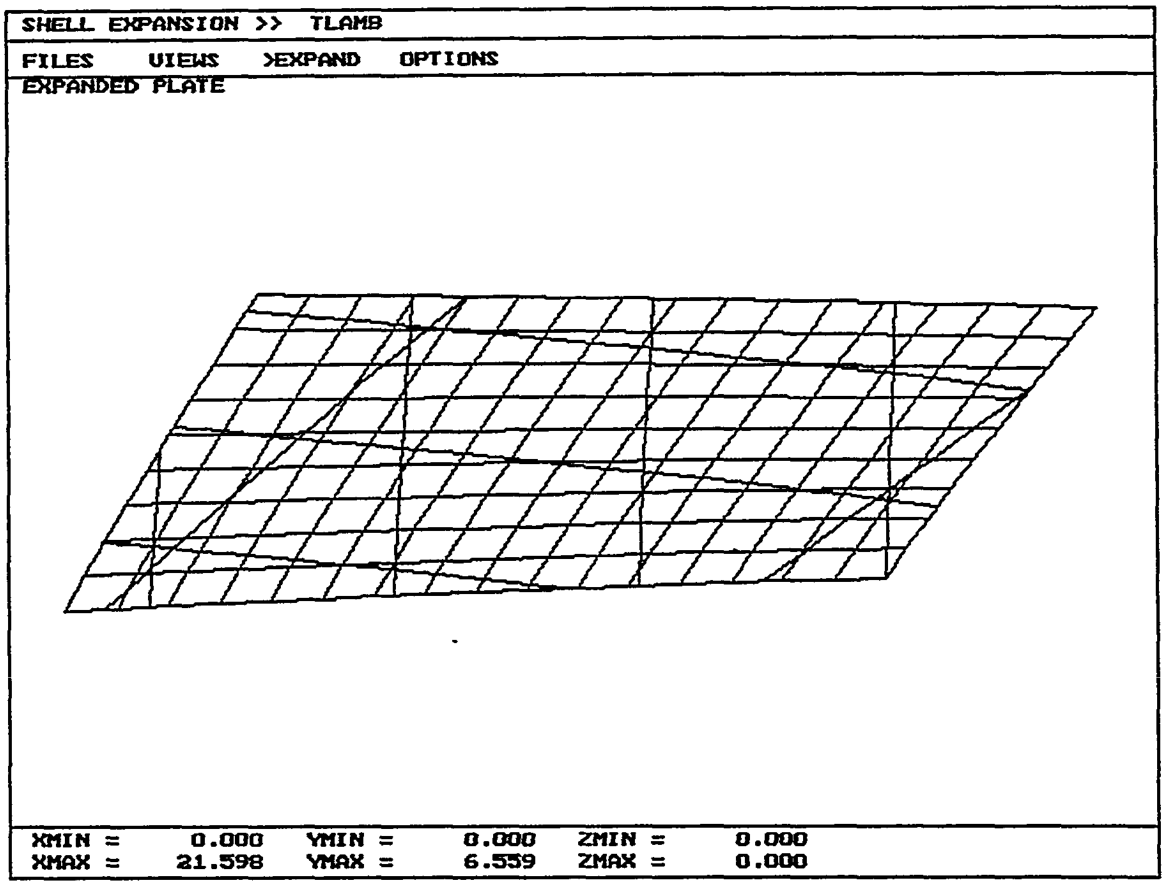


Figure 7: Expanded plate rotated bottom of screen lists the plate size

2.2.11 Saving the expanded plate

The geometry of the expanded plate has to be saved to disk for further operations. The following geometries are available for further operations after saving:

- the expanded surface mesh in 2-D space
- the markings parallel to the water line plane in 2-D space
- the markings parallel to the buttock line plane in 2-D space
- the markings parallel to the frame line plane in 2-D space
- a closed polygon for the plate outline in 2-D space

- a DXF formatted file with cross-hatched areas indicating expansion related in 2-D space deformations
- the surface mesh in 3-D space

The closed polygon can be readily used for burning the outside of the plate. The markings are used for the scribing unit. The strain map may be plotted and used by during the plate forming process. The 3-D mesh of the plate may be used for the production of assembly jigs.

2.2.12 Further plate handling

All expanded plates are now exported to the CAD program. Figure 8 shows four expanded plates that have been imported to AUTOCAD and layed up longitudinally as they are arranged on the hull. The plates can now be arranged and nested with any other parts of the hull, to utilize the available stock best. Albacore's NC-Pyres program can then automatically convert the CAD drawing to NC-code including automatic path optimization.

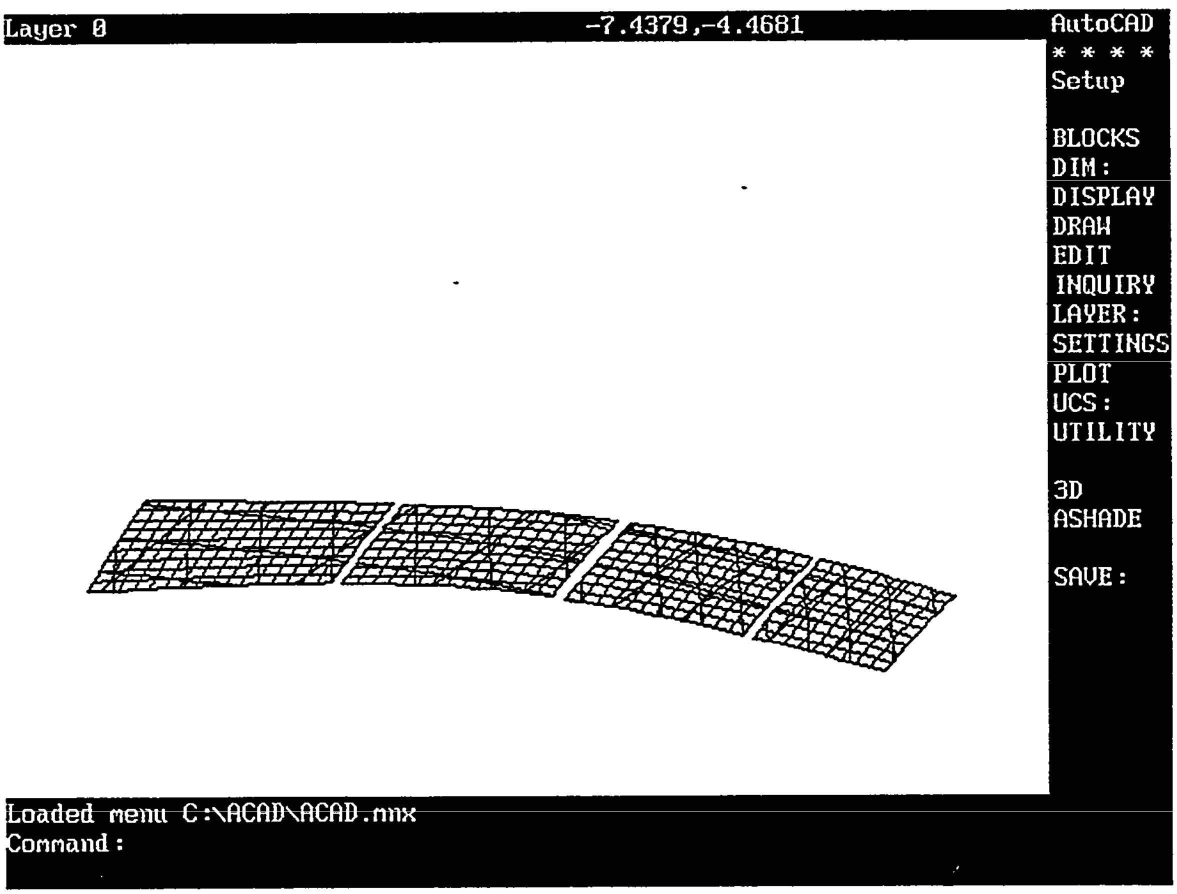


Figure 8: Example of nested plates in Auto CAD

2.4 Methods Used

2.4.1 Triangulation

A 3-D surface mesh is the input for the expansion algorithm. Each mesh element consists of four vertices on the surface mesh. The four vertices are connected by straight lines in 3-D space. Each mesh element can be further divided into two triangles. The algorithm finds a conveniently located mesh triangle close to the center of the surface mesh and transforms it from the 3-D space to a 2-D space. The algorithm moves through all mesh triangles from the center towards the outer edges and transform all triangles from 3-D space into 2-D space using a cosine-law triangulation method.The implemented algorithm proceeds over the surface mesh in such order, that any necessary deformations will occur along the longitudinal boundaries of the mesh elements, while the transverse oriented boundaries retain their initial length.

2.4.2 Strain map

The operator needs an indication for the complexity of the plate to expand. There are undoubtedly experienced loftsmen that can 'see' immediately if a plate can be formed with the procedures used by the yard. With the ShipCAM3 expansion module Albacore provides a unique visual aid for the operator to decide whether an expanded plate contains too much deformation to be shaped properly.

The longitudinal length differences between each expanded mesh element in the 2-D space and the same element in 3-D space are calculated. The deformations are set into relationship with the original lengths. The resulting values are defined as the deformation strains inherent to the mesh elements. Each element may experience stretch or compression. Strain values are represented as color filled mesh elements on the screen (see Figure 4 for a black and white example of a strain map). The maximum allowable deformation, i.e.maximum color, is given by the material properties, material thickness and the forming procedure used by the yard. The maximum strain has to be found empirically by the yard.

B KNOWN SHELL DEVELOPMENT PROBLEMS

The shell expansion program is relatively new. Albacore does not have extensive experience with general shell plating problems in industry.

The most difficult part of the process is not the shell expansion, but creating a fair hull surface to the architect's specifications. The fairing process, although supported by many visual aids, is still a time consuming and skill depended task. While it is easy to fair chine vessels, vessels with compound curvature hull shapes can be difficult to fair. In particular it is difficult to fair bulbous bows and transoms with integrated propellor bossings to a set of given offsets. However, if the vessel was designed using a computer ship design program, the fairing may be avoided The surface mesh directly from the ship design program

It may still be necessary to treat forward or aft section of a hull in a special manner for proper plate expansion results. This procedure is recommended when the transverse mesh lines show extreme fore/aft deflections (See Figure 9). The deflections produce highly curved seams. For the shown area (all white) it is not possible to select an adequate plate shape for the shell expansion.

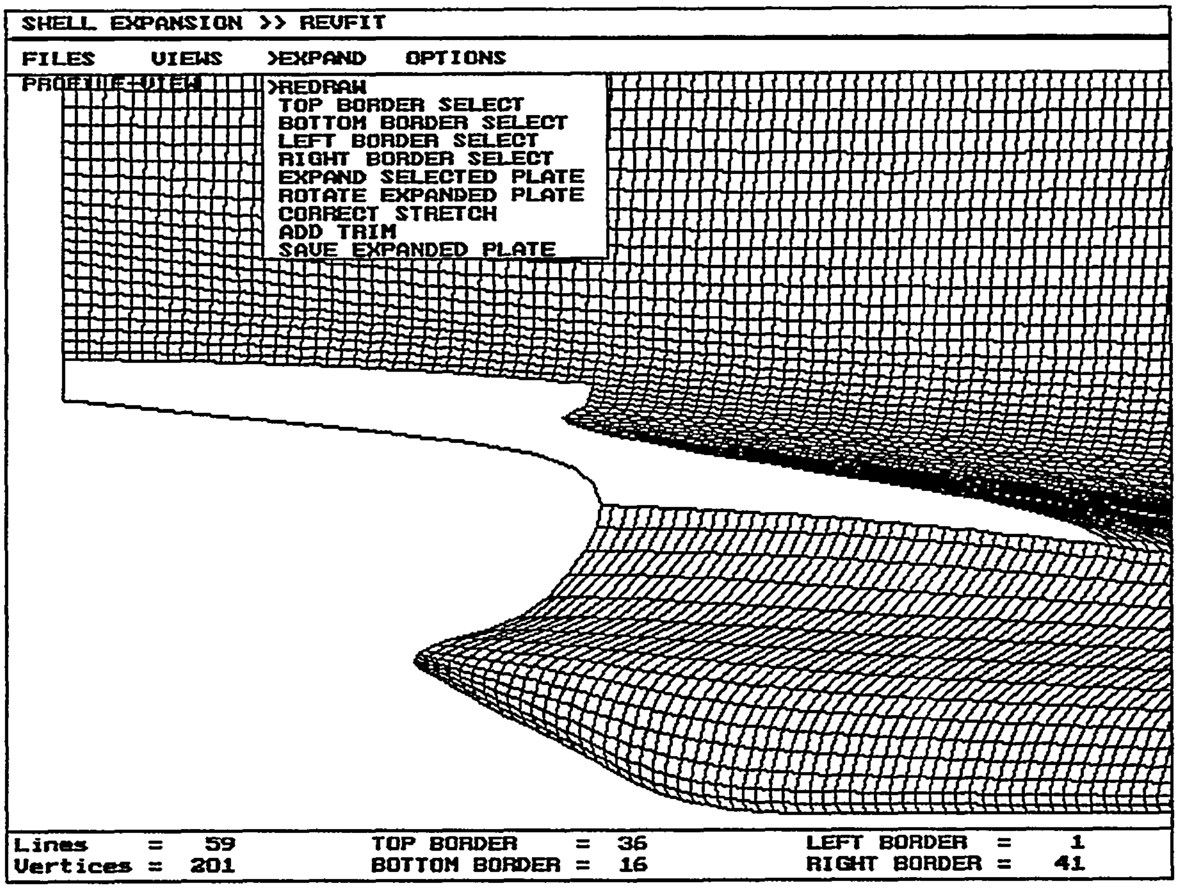


Figure 9: Stern of vessel with extreme fore/aft deflections in transverse lines

To overcome this problem a number of closely spaced sections are calculated on the hull and a surface mesh is fitted to the sections. The resulting mesh does not contain any deflections and can be expanded producing regular seams and butts.

C. LIMITATIONS OF SHELL DEVELOPMENT

1 Limitations regarding plate geometry

The program will expand any plate that conforms to certain guide-lines.

- The plate has to be approximated by a surface mesh of sufficient resolution.
- The mesh elements should be regular shaped. Extremely deformed mesh elements may cause the algorithm to produce irregular results.

There are no known limitations such as:

maximum or minimum length
maximum or minimum width
plate thickness
maximum back set
minimum curvature in any direction
limit of twist
ratios of back set to length
ratio of curvature to width
ratio of minimum curvature to thickness

3.2 Practical field limitations

The ShipCAM3 shell expansion module has been in use for less than a year. A few hulls have been expanded and built with it or are currently under construction. Clearly Albacore cannot look back at many years of experience with the shell expansion program. Testing on models, comparisons with manually lofted plates by experienced loftsmen and three production hulls give Albacore confidence in the results the software produces.

3.3 Limitations regarding operator assistance

The beta version did not provide sufficient information for the operator to discover potential problems. On one occasion a straight section surface was expanded which contained a large amount of twist in the bow area. The expanded plate showed strains on the full length along the upper and lower plate edge which where right at the upper tolerance level. Also the number of longitudinals was too small to represent the complexity of the plate with sufficient resolution.

The resulting plate was too short on the edges when fitted to the ship structure. Since then the expansion module has been enhanced to detect problems like this. The program now lists the total longitudinal deformation which allows the operator to make a more informed decision. Also capabilities of correcting the sttetch automatically and adding trim automatically have since been added.

3.4 Limitations regarding plate thickness

The shell expansion is currently calculated for the mold line. A planned upgrade for this year will allow to perform shell expansions for surfaces that are corrected by half of the shell plate thickness. Negative thickness will be allowed as well to correct for hulls that are lofted on the outside of the plating.

3.5 **Limitations regarding completeness of provided information**

The program currently does not provide an automatic function to provide information for assembly jigs, but it may be obtained with CAD programs. Also roll lines for forming information are currently not provided. However most of these informations may be obtained manually from the CAD program Automatic functions for all of these features are planned for the near future.

APPENDIX 10.1.2

BMT ICONS LIMITED REPORT

for Mr. Thomas Lamb, 4/ 3/92
Director Production Design

PART A: DESCRIPTION OF BMT CORTEC SHELL PLATE DEVELOPMENT METHOD

BRIEF DESCRIPTION

The shell development algorithm is a modified two-dimensional multiple triangulation approach which commences at an identified convenient centre of the plate. The algorithm is used progressively and works in general terms up and down to both seams and forward and aft to both butts. Up to eight-sided plates can be handled.

Some parts of the BRITSHELL code are particularly well established; other parts are more recent. The basic software has been in practical use for about 20 years. The triangulation process has been recently modified to take benefit from the fact that the input data are now equi-girthed on frames. Furthermore, spline curve fitting has been introduced for the row, column and diagonal girth calculations, with due regard for frames with associated knuckles. Previously the triangulation Was more random.

A three-dimensional surface definition is used as the basis from which to derive the necessary shell plate characteristics. An appropriate net of surface points is used to transfer the plate data to the shell development algorithm. The alternative of directly referencing one or more B-spline patches in a re-definition of the local surface has been considered but not adopted because of the complexity of the general case of an n-sided plate.

The user is provided with the ability to assess the fairness of curves on the surface, and the curvature of the local surface itself, so as to identify a convenient plating arrangement which caters for, and perhaps isolates, regions of double curvature.

The algorithm provides methods to develop frame, waterline and internal structure traces with the shell plate as well as an average or detailed roll line for each plate. A sight line can optionally be marked as a check, together with frame sets information, for the correct forming of the plate.

The approach also provides checking dimensions for manual verification of the developed plate and its markings.

DETAILS OF THE ALGORITHM USED

The following is a detailed description of the algorithm used in the BMT CORTEC SHELLDEF/BRITSHELL approach.

1. The surface definition used by SHELLDEF is an aggregate of hi-cubic B-spline patches, any number of which may be used to define a surface. Typically 50 patches are employed for the symmetric half of a conventional hull . An example patch arrangement for a trawler is shown in Figure 1.

The surface is the product model available from the interactive BMT BLINES design/lines fairing system and the HULLSURF surface definition system.

2. The SHELLDEF system is used interactively to define points and build up sets of surface curves. The co-ordinates of a point on a specified section, waterline, buttock or more general 2D planar intersection can be obtained either by cursor selection or by keying in identifying section data. Reference can optionally be made to relative girths from other crossing points or tunes. Tangent and knuckle points can be defined. A tune can be defined as offset from a previously defined curve. By definition, the curves will lie on the surface. Figure 2 illustrates a set of surface curves in section view and Figure 3 shows the curves in a convenient oblique view.

3. The user can assess the fairness of the surface and of the surface curves using a variety of curvature facilities. Positioning of seam curves can then be made with reference to the available surface curvature information so as to identify those regions which exhibit excessive double curvature.

4. Seams can be defined based on the aggregate of a set of named tunes defined as above and held in the datastore. The seams are used by the SHELLDEF STRAKE or UNIT and PLATE commands to then define the plates of the surface. Each seam is defined as a set of curve names and reference X or frame positions. Up to the first specified position, the first named tune is effective, etc. for as many distinct tunes as may be appropriate. Each so defined transition point of the seam is taken to be a knuckle point for the subsequent plate definition. A directory of seams information can be obtained.

5. Each plate of the STRAKE or UNIT is defined with reference to two butts , each of which may be a single point, and a lower and upper seam curve, each of which may contain up to two knuckle points. Thus plates may be up to eight-sided.

6. During the interactive definition of a plate in SHELLDEF, any local surface cuzves, such as profiles of decks, bulkheads and longitudinal, are automatically detected and interpolated on frames or waterlines to form part of the subsequent plate marking data.

7. A facility exists whereby an auxiliary surface is generated and an intersecting sight line is automatically calculated; this intersects the mid-girth positions of the butts and lies along a plane inclined at an average angle normal to the tangents of the butts. The sight line is stored as a special marking curve and is used subsequently in the shell frame sets information to construct an auxiliary viewing plane and to provide some checking distances for the correctly shaped plate.

8. A net of surface points is used in the transfer of 3D data from SHELLDEF to BRITSHEIL for calculation of the 2D developed plating and associated production information. The definition of a plate based on one or more B-spline patches has been considered, but not adopted; in any case this alternative approach would involve some re-definition of the local surface which could be quite complex for some plates, e.g. where the plate

edges are highly shaped or in regions of significant curvature.

9. The SHELLDEF system permits the user control over which frames are used to define the net of points. Points up each frame are based on equi-girth distances. During the triangulation process in BRITSHELL, the user is warned of any excessive variations of aspect ratios. Sufficient intermediate frames are automatically introduced so as to give a minimum of ten defining frames. This has been found to be satisfactory for most cases; in special situations, e.g. to hold a highly shaped seam, additional frames are previously drawn by the user and the SHELLDEF system then automatically includes all such frames (held in the directory of drawn frames) in the plate definition.

10. Based on the above net of (3D) surface points, splines are defined across the frames for each row of points. These secondary splines will contain knuckle points at each of the knuckle frames (if any).

11. Plates are developed with respect to their mid-thickness surface; negative thicknesses may be specified. The net of frames data from SHELLDEF is assumed to represent the moulded surface, thus in BRITSHELL these data are first corrected for the thickness of the material before the development process is commenced.

12. To begin the triangulation process, a central pair of adjacent frames is identified, with due regard to the position of the knuckle frames, and developed. Next a central row pair is developed. The development process is a triangulation which is based on girths calculated between adjacent points of the net, including a set of diagonals in the two central bands; one in the direction of the frames and the other across the frames. See Figure 4.

13. For each triangle processed, the user is warned of possible high aspect ratios of max/min lengths of sides and/or the max/min angles of the triangle. If warnings of such severe triangulation occur then it may be advisable to define additional frames in SHELLDEF (simply by drawing them) and to then repeat the plate definition and development.

14. Independent triangulation of the four remaining portions of the plate (see Fig. 4) is then carried out using a method that tends to preserve the overall seam and butt girths for matching of adjacent patches. An example developed shell plate is shown in Figure 5. A roll line is calculated and drawn; this indicates the preferred way in which the plate should be presented to the roll press.

15. Special consideration is given to the possible occurrence of single point aft and forward butts and also to the possibility that a frame is shorter than a specified tolerance.

16. The processing of each plate comprises the following modules:

- DEVELOP; calculation of 2D plate information,
- MARK; calculation of 2D marking information,
- GREEN; optional addition of green material,
- RECTANGLE; calculation of the minimum rectangle,

- PLATE ; graphical checking information or output of production data,
- SETS; shell frame sets output data.

Plate checking dimensions are calculated. These are defined in Figure 6 and form part of the numerical output for each plate after the calculation of the minimum rectangle.

17. A production mode is defined which determines whether the output is graphical or in optical following, ESSI or possibly EIA formats. The above modules are each processed for a specified batch or unit of plates; usually the /PROCESS option is specified for the DEVELOP command and this causes the modules to and including the PLATE command to be activated.

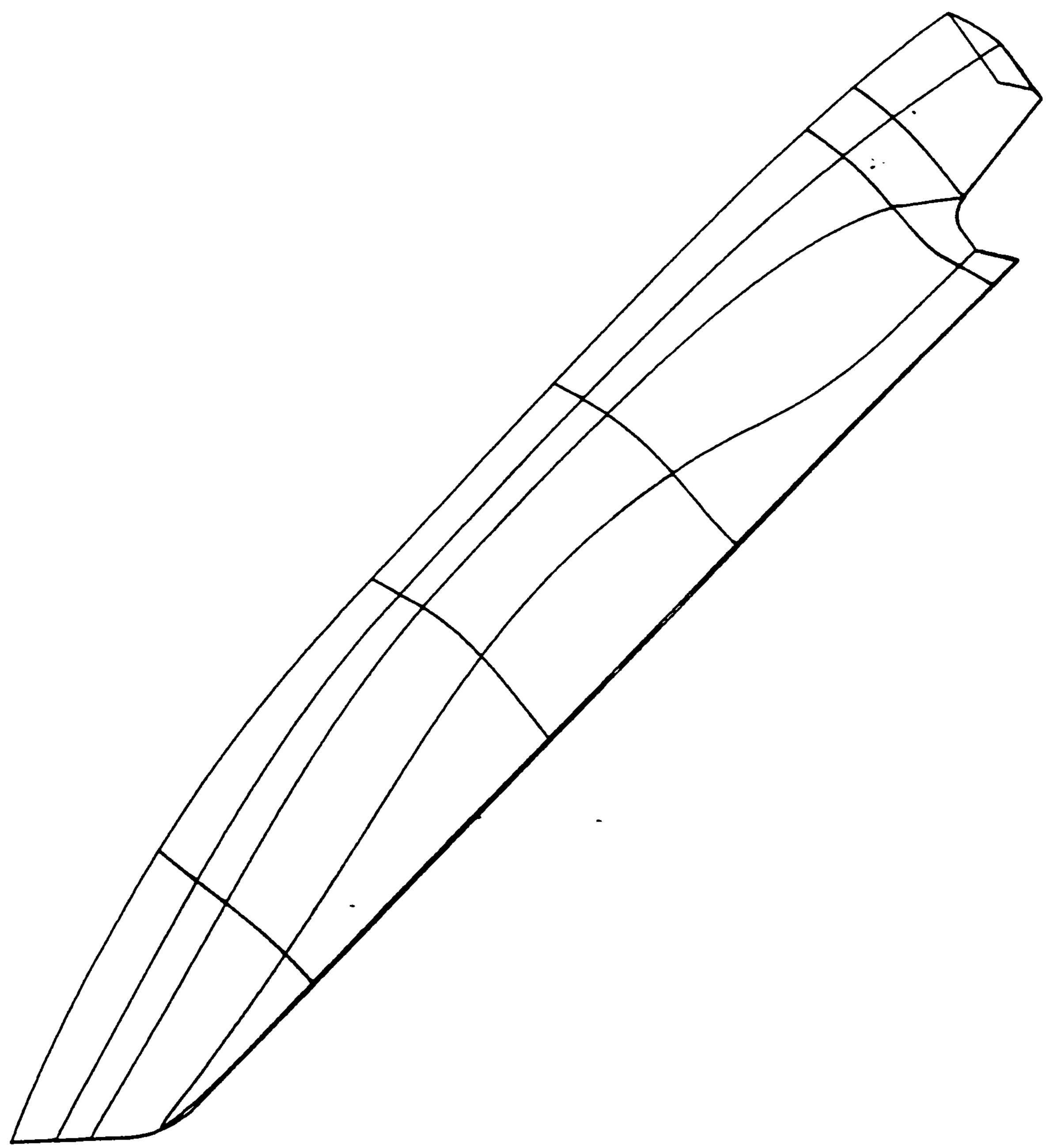
18. For a given plate, there is a choice as to the set of frames which are to be drawn so as to provide the necessary forming information. Figure 7 shows typical roll sets corresponding to the plate of Figure 5. The viewing plane used to check the plate forming process is illustrated in Figure 8. Templates as in Figure 9 can be constructed, out of wood for example, to provide a physical checking process.

19. Assembly jigs information can be calculated for a unit of one or more plates. Output is both graphical and numerical. In addition to an accurate calculation of the jig pillar heights, checking distances to a reference pin and the plate edges, plate corners, etc. are provided. Figure 10 shows an example assembly.

20. The above definition of the plates is used for the plate development process. However, the subsequent jigs; sets and inverse bending calculations are carried out with direct reference to the SURFACE data held in the HULLSURF datastore. Optionally, the plates data, rather than the surface data, can be-used to generate the sets information so as to speed up the calculation in less complex regions of the surface.

21. The SHELLDEF and BRITSHELL systems enable the user to define input and output units which may be different. For example, the product model may be defined in feet units with plates being output in metres.

22. Access routines for a plates datastore are available to the user in the same way in which, for example, BLINES and HULLSURF access routines are used to obtain surface section data. These routines allow the user to interrogate the appropriate part of the total datastore for specified data items.



Note: flat of side (FOS) boundaries are natural but optional. Similarly the flat of bottom may be used to define patch boundaries.

Fig. 1 Example Patch Arrangement for a Trawler

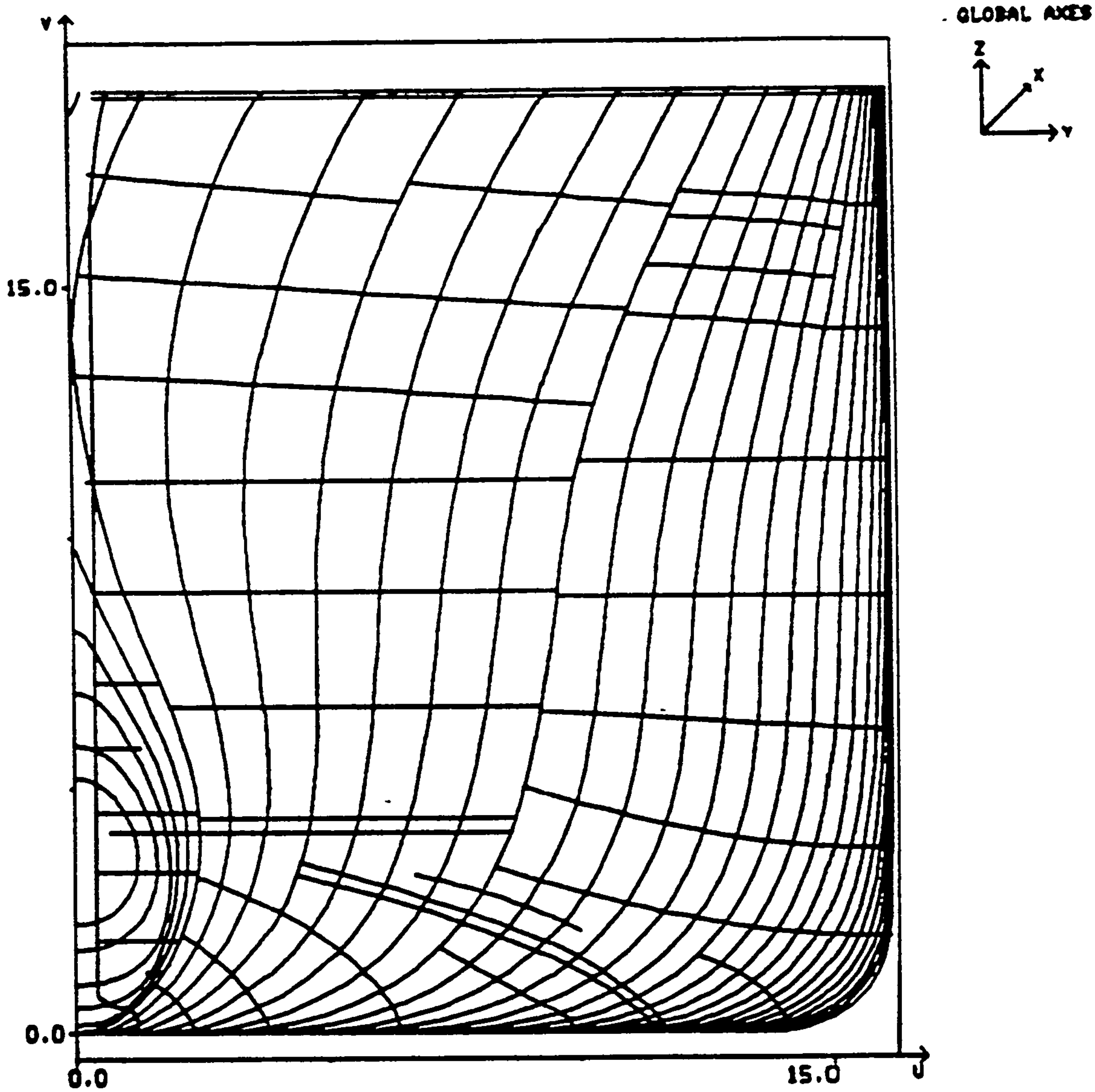


Fig. 2 Example Surface Curves; Section View

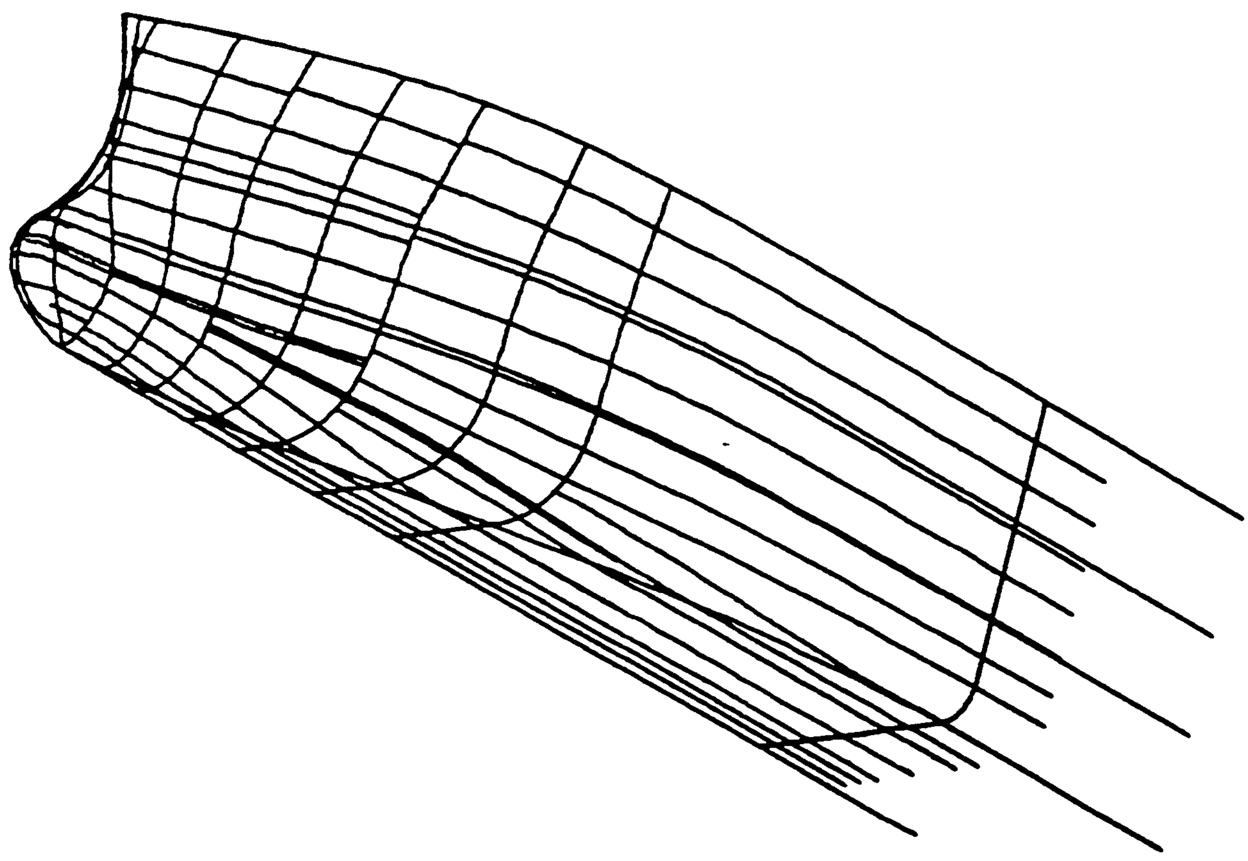
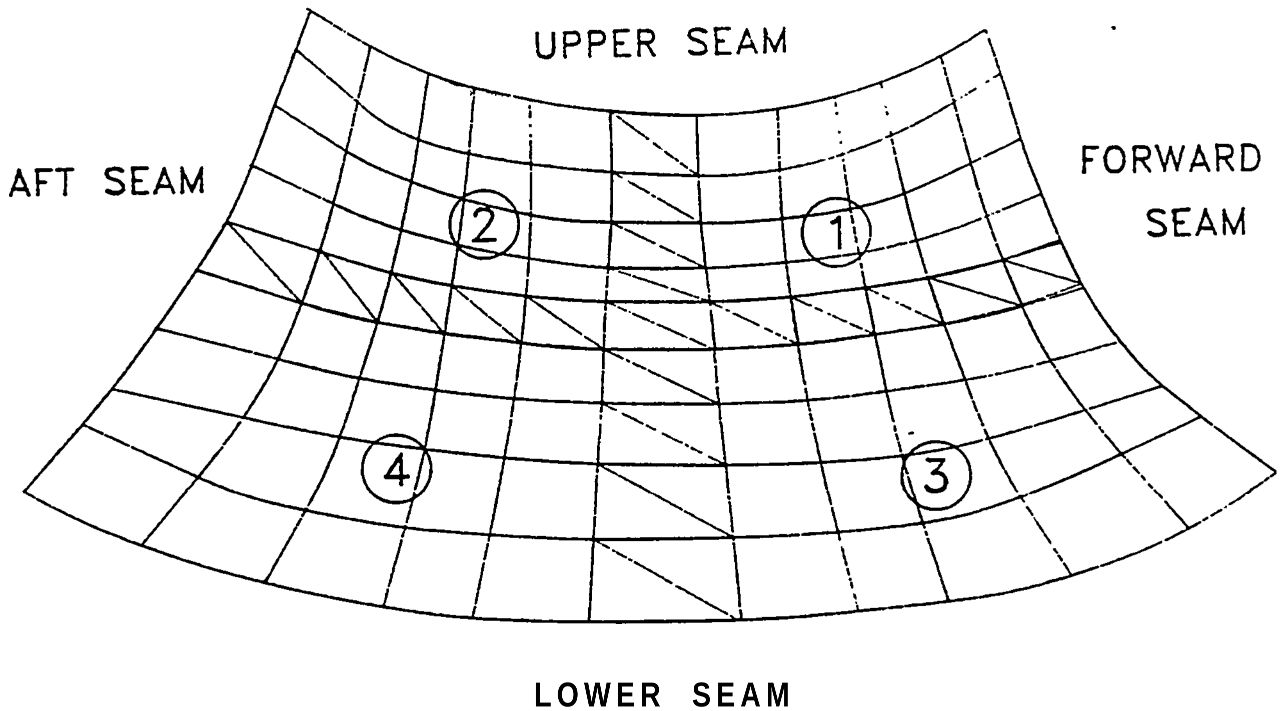


Fig. 3 Example Surface Curves; Oblique View



Procedure:

1. Define appropriate central frame with regard for knuckled seams.

2. Fit splines to frames and for curves across frames to obtain girth data.

3. Develop first triangle based on calculation of diagonal girth using a local spline fit to data.

4. Develop triangles of central column.

5. Develop triangles of central row.

6-10 Develop regions 1 through 4.

Fig. 4 Sketch of the BMT Triangulation Approach

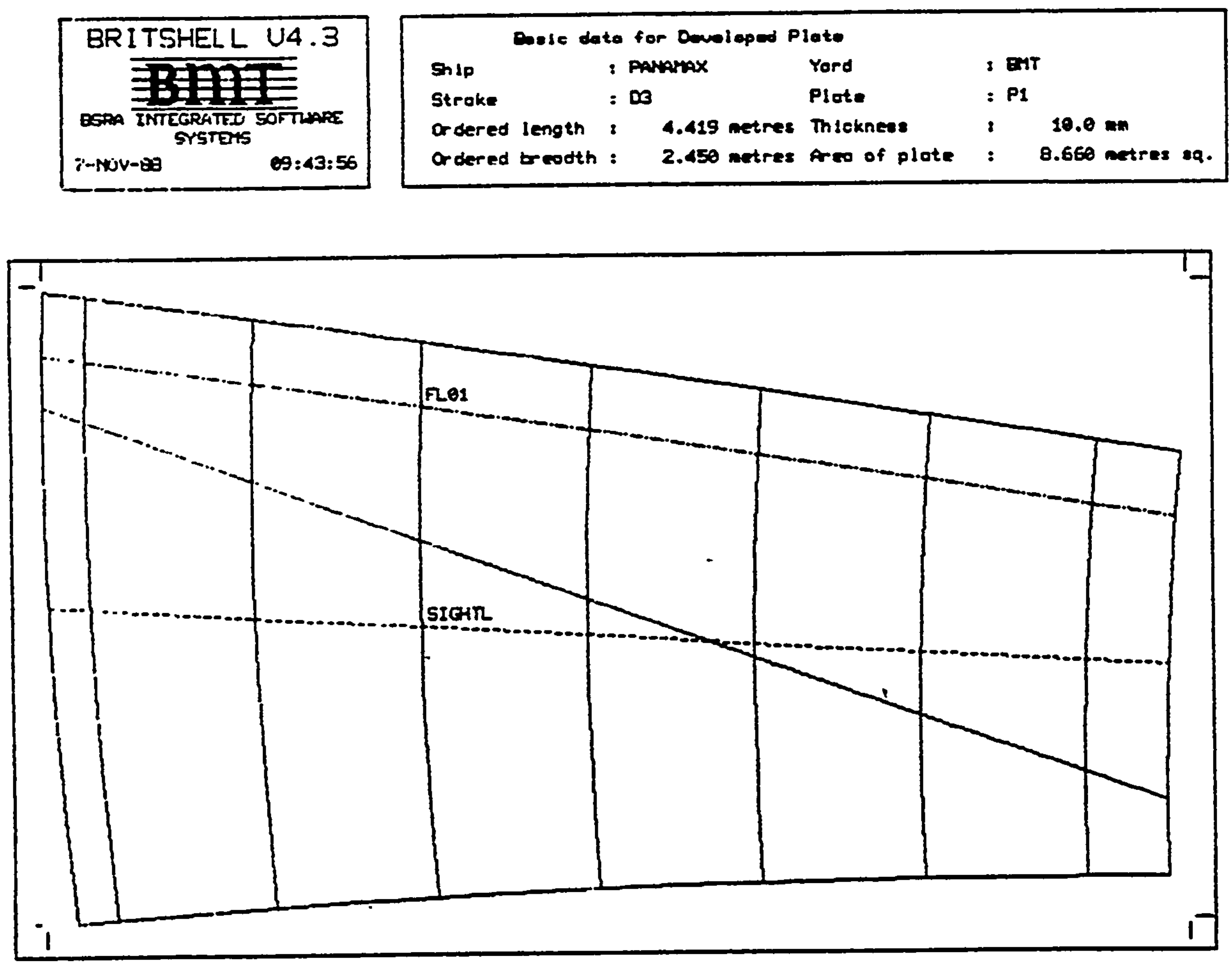


Fig. 5 **Example Developed Shell Plate**

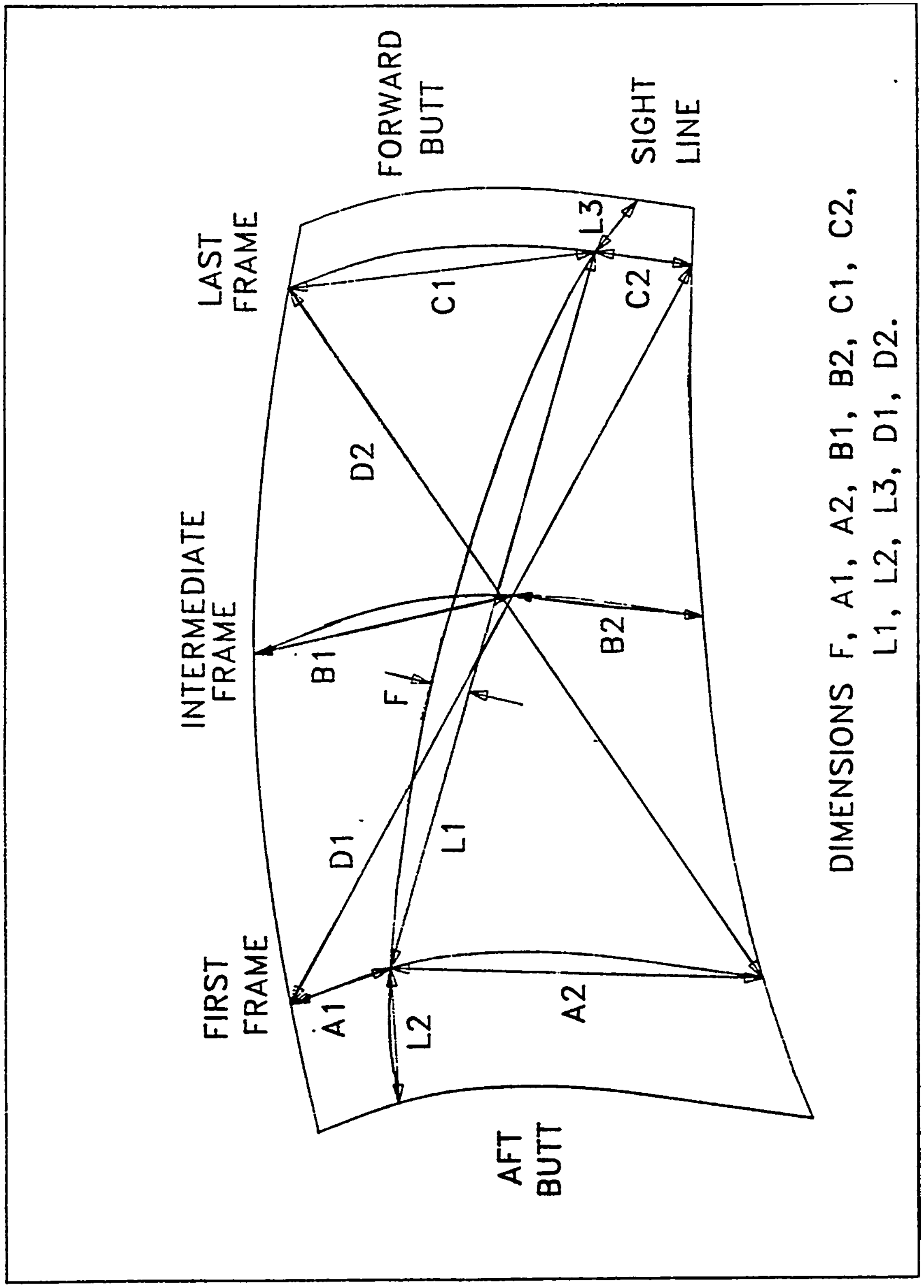


Fig. 6 Definition of BMT Plate Checking Data

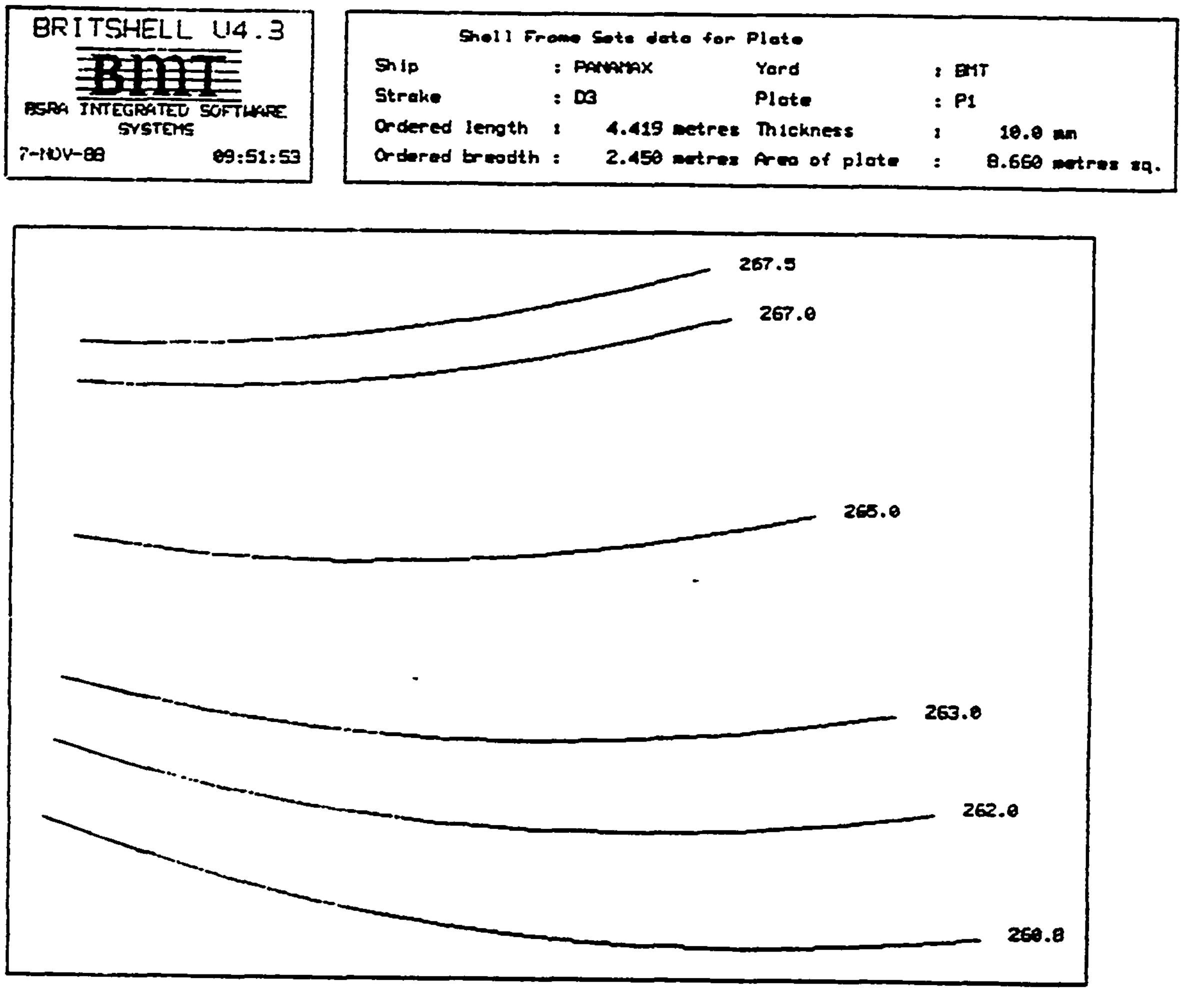


Fig. 7 Typical Roll Sets

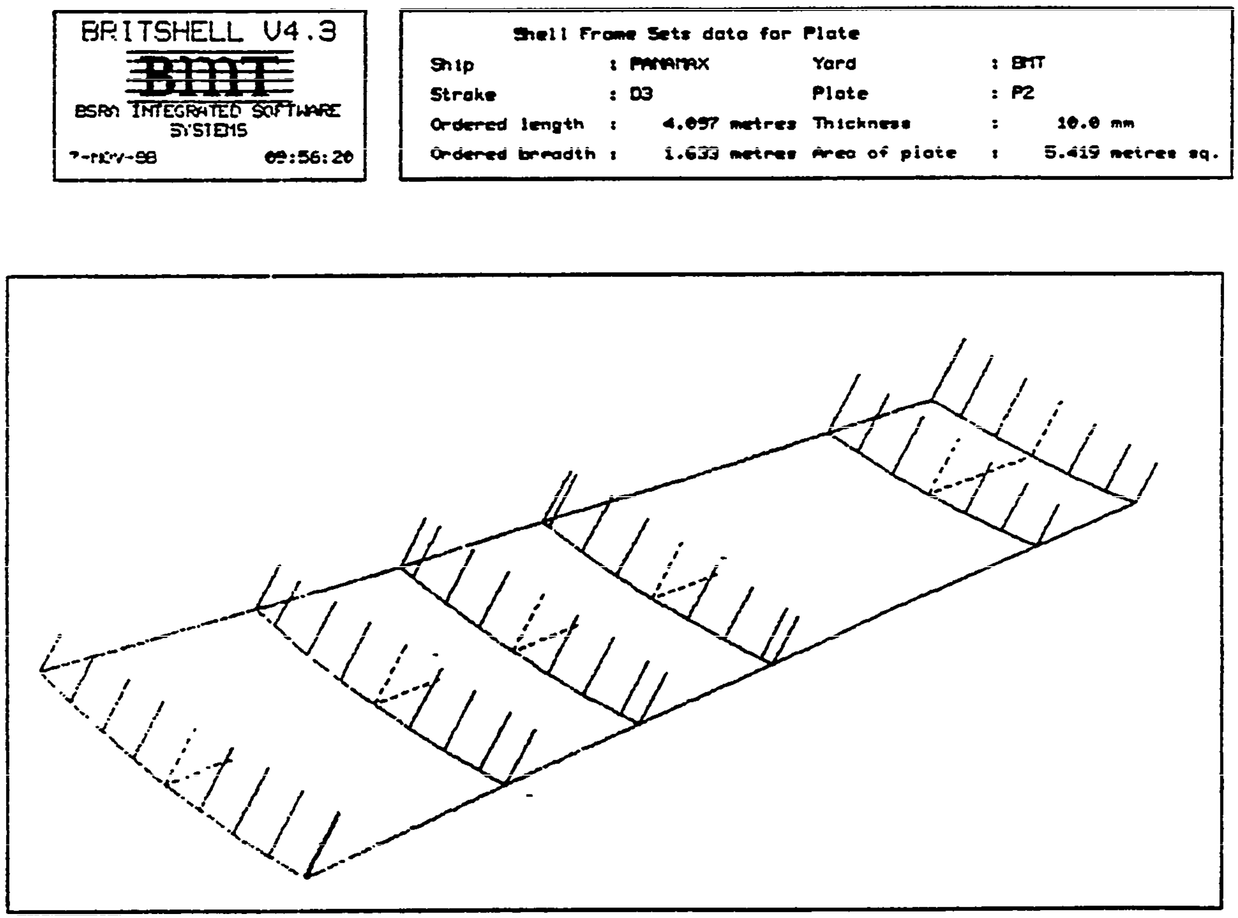


Fig. 8 Example Viewing Plane for Correct Forming of Shell Plate

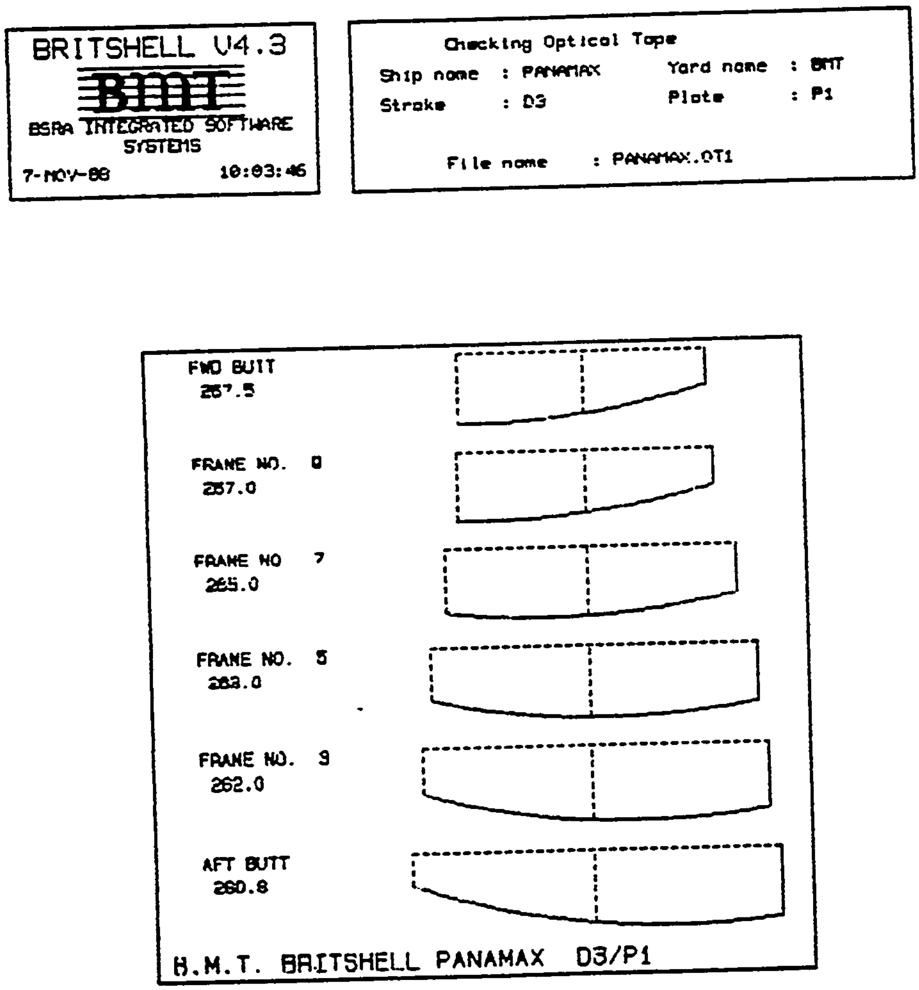
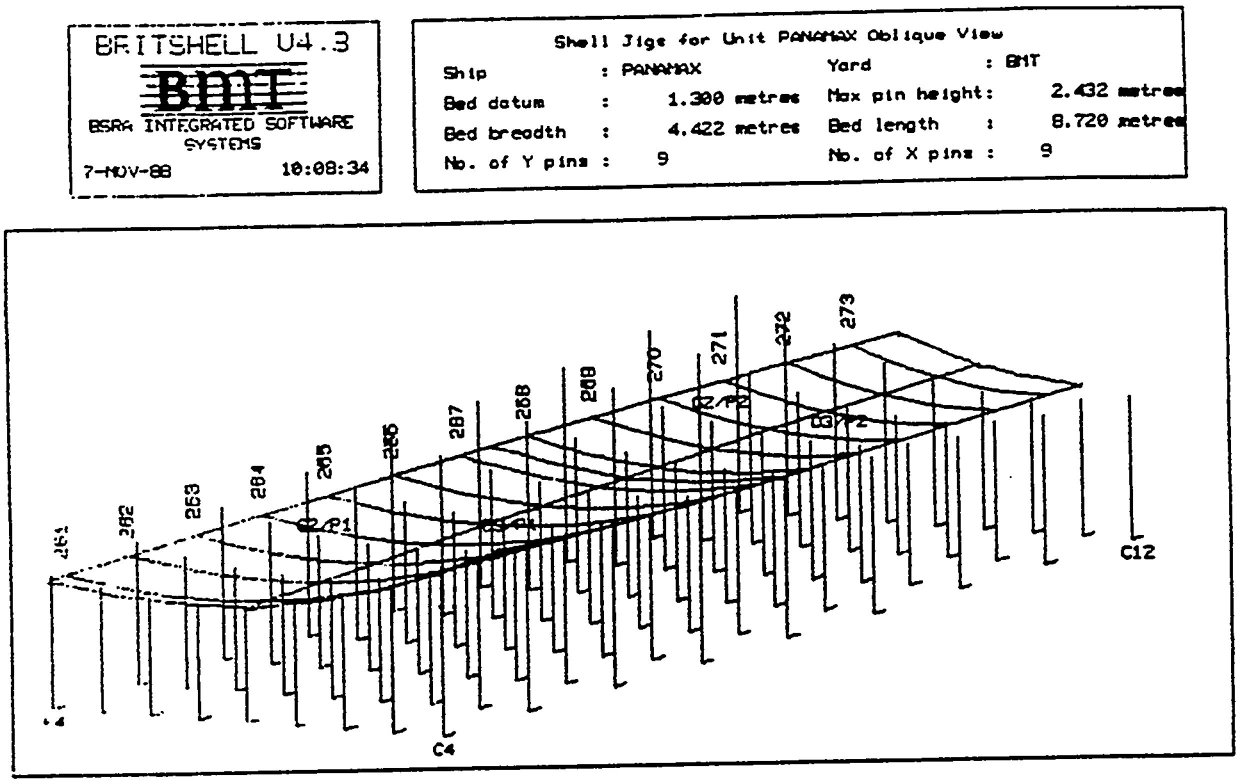


Fig. 9 Optical Following Information for Construction of Templates



The JIG Bed in Oblique View with Frames

The JIG Bed in Plan View with Frames

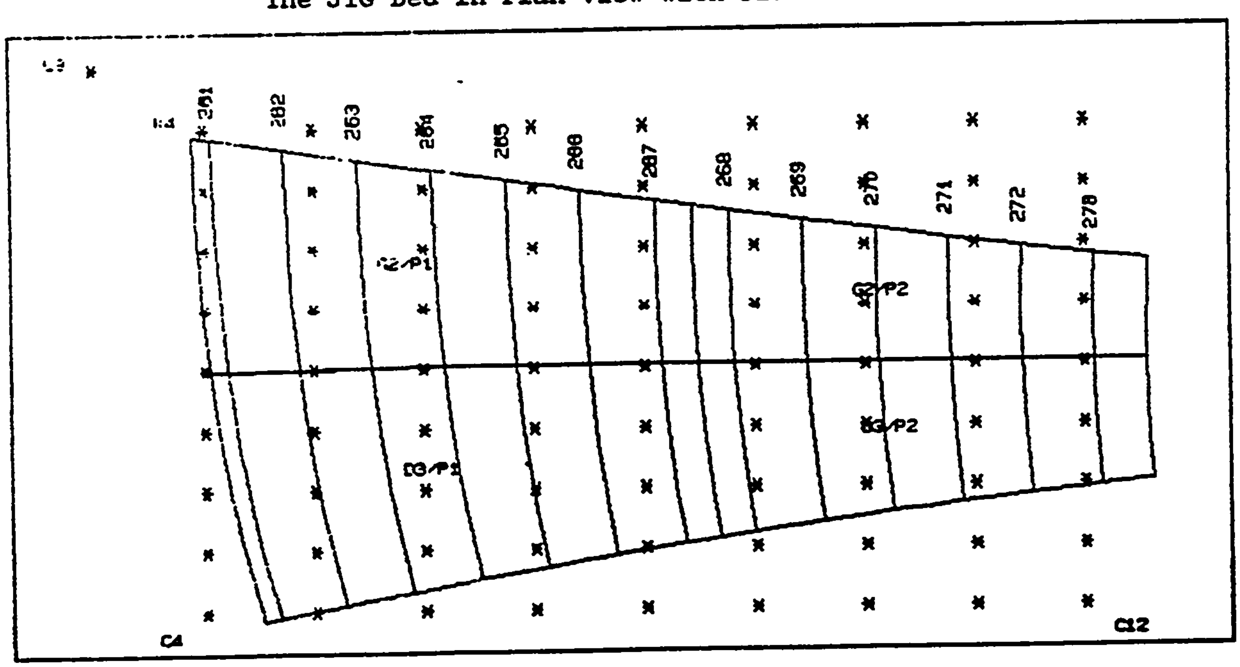


Fig. 10 Example Jig Assembly Graphical Output

SNAME SPONSORED LOFTING PROJECT

Ref: 3920229 .R02

for Hr. Thomas Lamb,
Director Production Design

31/ 3/92 .

PART B: DISCUSSION ON USE OF BMT CORTEC SHELL PLATE DEVELOPMENT METHOD

INTRODUCTION

The BMT CORTEC approach to shell development is described in Report 3920299.RO1 which gives details of the algorithm used. The software systems are designated SHELLDEF for the interactive definition of the three-dimensional shell plating and BRITSHELL which includes the development algorithm.

DISCUSSION

When developing shell plating, there are certain areas of a ship where the development of-the surface may cause problems and therefore these areas require careful consideration. The problem areas which occur most often are:

- wherever double curvature of the plating arises, especially in the region of stem/stem bulbs,
- plates adjacent to the stem in way of the load waterline,
- plates adjacent to the stem between the top of the bossing and the load waterline.

The regions of double curvature, and the direction and magnitude of the curvature in these regions, can be ascertained using the SHELLDEF plate definition system by displaying tufts of principal curvature for the surface patches. The seam definition in these regions should then be defined with particular care by experienced loftsmen in the shipyard and with due regard to the production constraints. These constraints are typically the maximum dimensions to which the shipyard can roll OR heat-line bend any given plate (Please refer to the Report for Part C).

Within the SHELLDEF plate definition system, it is usual to add more frames to the above mentioned shell plate areas prior to their development in the BRITSHELL program.

In the current release of the software, the surface in the region of a soft nose or transom must first be transformed so that seams can be conveniently defined with respect to a new X axis for the controlling direction. This modest inconvenience is being eliminated with the introduction and testing of some new facilities.

Provision of excess stock, designated in BRITSHEIL as green, is available. Green is allowed on the plates edges or butts to the requirements of the shipyard's unit construction. Green can be specified independently on each of the (up to eight) sides of a plate.

Checking dimensions are provided for each developed plate, see Fig. 6 of the Report for Part A. The shell frame sets information includes the option of a sight line viewing plane (Fig. A8) and data for the construction of templates (Fig. A9). Additionally, a tabular output of sets checking data can be obtained. An example plate is illustrated in Fig. 1 of the present report and a typical example tabular output is given in Fig. 2.

Jig assembly information includes a table of the pin heights, see for example Fig. 3, and checking distances along the seams and to the plate corners, see Fig. 4.

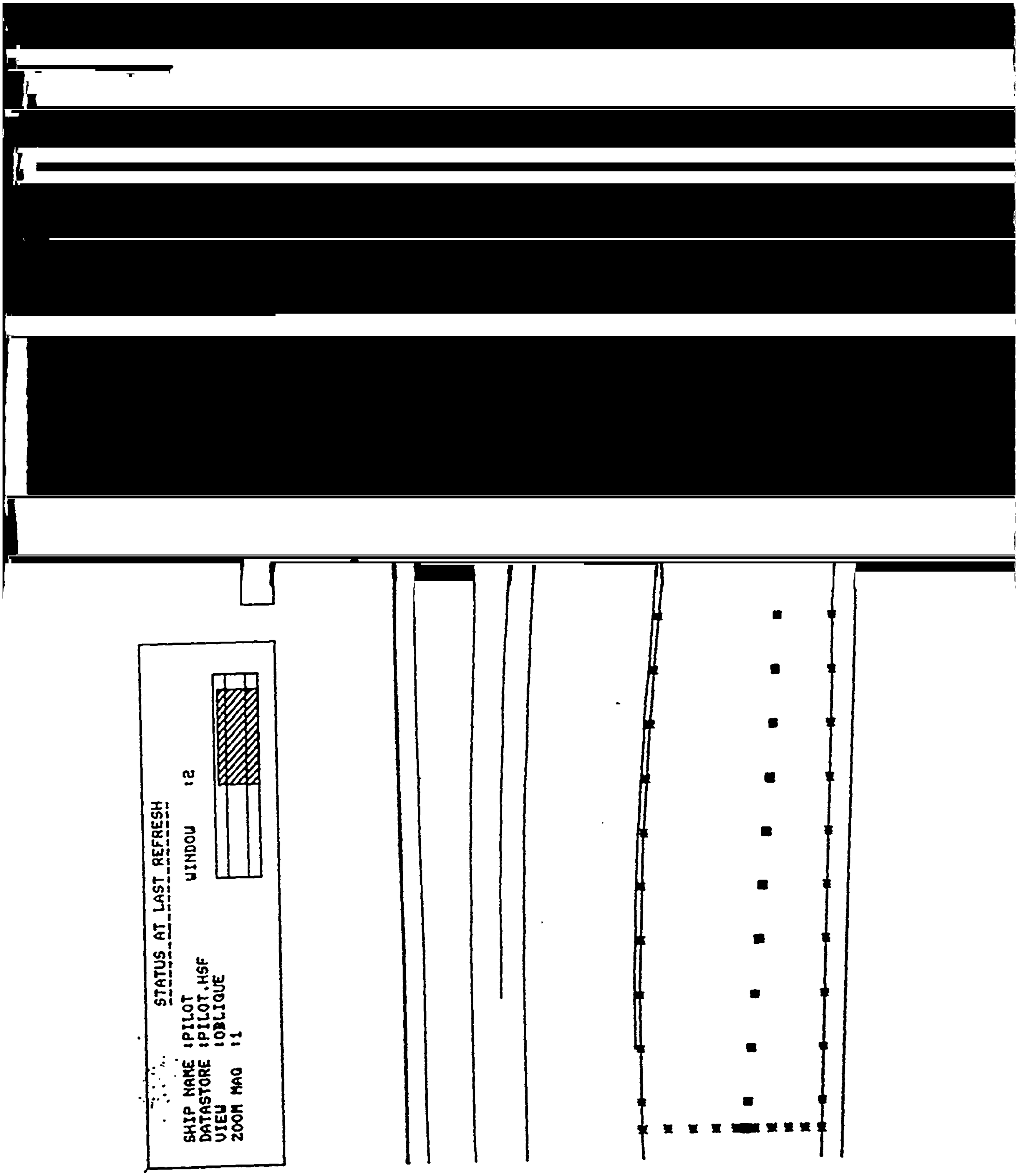


Fig. 1 Example Plate with Sight Line Marked

BMT CORTEC Ltd. 3920229.R02

Strake name D3 Plate name PI Plate No. 1

Distance from Sight Line	Frame metres	260.750	261.500	263.000	265.000	267.000	267.500
	Angle	70.8	109.4	110.0	110.6	111.1	111.2
-2000	A						
-1800	B						
-1600	C						
-1400	D						
-1200	E						
-1000	F	267	295	342			
-800	G	325	347	384	418	439	
-600	H	374	391	416	435	441	442
-400	I	414	430	440	444	436	432
-200	J	446	452	455	445	422	415
Sight Line		469	469	462	438	400	390
+200	K	484	479	462	423	371	357
+400	L	491	482	454	401	335	317
+600	M	491	477	437	372	291	270
+800	N	484	465	416	336	241	215
+1000	o	470	446	387			
+1200	P	450					
+1400	Q						
+1600	R						
+1800	S						
+2000	T						
Upper seam height		448	424	372	300	231	214
Upper seam dist		1213	1174	1090	968	837	804
Lower seam height		212	261	338	405	439	443
Lower seam dist		1168	1115	1017	904	812	792

British Maritime Technology Limited

shell Development System BRITSHELL sets Essi Development Module
output for ship PANAMAX on 19-Jul-88 at 14:34:31
Lengths and co-ordinates are in mm

Fig. 2 Example Tabular Output for Sets Sight Line Information

British Maritime Technology Ltd. Shell Jig Information Produced at 09:40:15 on 1-Apr-92
Ship : BULB1 Maximum pin height 2396
Unit name : TEST1 Datum pin height 1000

Table of Pin Heights (mm) --Page 1

Pin	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
M	1959	1913	1870	1834	1806	1787	1775	1778	1788	1836	1951	2184	0	0	0
L	1741	1699	1654	1609	1564	1520	1479	1450	1439	1456	1514	1631	1842	2396	0
K	1567	1525	1482	1437	1388	1339	1295	1262	1246	1253	1292	1376	1531	1835	0
J	1432	1392	1349	1305	1257	1210	1169	1137	1121	1125	1158	1234	1376	1633	2302
I	1332	1293	1253	1211	1168	1125	1086	1055	1039	1045	1084	1168	1321	1587	2186
H	1264	1228	1192	1153	1114	1075	1039	1011	1000	1013	1062	1161	1339	1642	2304
G	1228	1196	1163	1129	1093	1058	1027	1006	1001	1022	1081	1198	1405	1757	0
F	1222	1194	1165	1135	1103	1073	1048	1034	1037	1067	1137	1271	1509	1921	0
E	1245	1221	1197	1171	1144	1120	1101	1093	1104	1144	1226	1378	1650	2160	0
D	1299	1279	1259	1238	1216	1196	1181	1179	1198	1250	1345	1519	1833	0	0
C	1385	1369	1352	1335	1318	1301	1289	1291	1317	1378	1486	1687	2082	0	0

Fig. 3 Example Table of Shell Jig Pin Heights

BMT CORTEC Ltd. 3920229.R02

British Maritime Technology Ltd. Shell Jig Information Produced at 09:40:15 on 1-Apr-92
Ship : BULB1
Unit name : TEST1

Plate Position Information (mm) -- Page 1

Position of Plate : S07/SB003

```
LA is  53 FWD of  4   100 I/B of C  113 from C   4  1053 FWD   5600 I/B and  5600 from N2  Height = 1389
UA is 161 FWD of  3     8 I/B of H  161 from H   5   661 FWD   3008 I/B and  3008 from N2  Height = 1252
LF is  79 AFT of 12    39 I/B of D   38 from D  11  4921 FWD   5039 I/B and  5039 from N2  Height = 1248
UF is  22 FWD of 11    52 O/B of I   56 from I  11  4522 FWD   2448 I/B and  2448 from N2  Height = 1045
```

Position of Plate : S08/SB003

```
LA is  79 AFT of 12    39 I/B of D   38 from D 12   4921 FWD   5039 I/B and  5039 from N2  Height = 1248
UA is 162 FWD of 11    56 O/B of G  171 from G 11   4662 FWD   3444 I/B and  3444 from N2  Height = 1002
LF is 405 FWD of 16    64 I/B of H  410 from H 16   7405 FWD   3064 I/B and  3064 from N2  Height = 2117
UF is 401 FWD of 16    47 O/B of H  403 from H 16   7401 FWD   3047 I/B and  3047 from N2  Height = 2105
```
-etc-

British Maritime Technology Ltd. Shell Jig Information Produced at 09:40:15 on 1-Apr-92
Ship : BULB1 - see also REC listing file Reference pin is N2
Unit name : TEST1 for plate frame girths Ref height on pin 3793

Frame Checking Table (mm) -- Page 1

Distances of frame point from ref pin Frame	Lower Seam Forward	Lower Seam Inboard	Lower Seam Height	Lower Seam Distance	Upper Seam Forward	Upper Seam Inboard	Upper Seam Height	Upper Seam Distance
284	1201	5578	1379	6196	550	710	1858	2133
285	1794	5492	1341	6277	1148	651	1830	2366
286	2387	5406	1300	6414	1747	596	1805	2713
287	2980	5320	1261	6603	2348	545	1789	3135
288	3574	5234	1227	6838	2952	504	1786	3605
289	4170	5148	1213	7109	3559	473	1797	4108
290	4770	5061	1235	7410	4170	455	1827	4632
291	5376	4973	1309	7733	4889	1711	1189	5798
292	5993	4883	1480	8069	5494	1623	1252	6267
293	6634	4790	1865	8407	6107	1534	1389	6740
294	7168	4032	2160	8385	6737	1443	1676	7207

Fig. 4 Example Seam and Plate Corner Checking Data for Jig Assembly

SNAME *SPONSORED* LOFTING PROJECT Ref: 3920229 .R03

for Hr. Thomas Lamb, 31/ 3/92
Director Production Design

PART c: RESTRICTIONS ON USE OF BMT CORTEC SHELL DEVELOPMENT METHOD

INTRODUCTION

The BMT CORTEC approach to shell development is described in Report 3920299.RO1 which gives details of the algorithm used. The software systems are designated SHELLDEF for the interactive definition of the three-dimtensional shell plating and BRITSHELL which includes the development algorithm.

SPECIFICATION OF LIMITATIONS

The approach has been used successfully in the building of ships and other surfaces for approximately 20 years- During this time a great deal of in-house and user expertise has been accrued in the application of the software. The software itself has undergone relatively minor changes which reflect an improvement to the quality of the definition of the host surfaces rather than any limitations of the algorithm used for the shell development.

Facilities exist for the rotation of plates to a convenient position within the minimum rectangle- The rotation may be based on either:

minimum area, or
minimum width, or
a specified angle-

Green allowances may be added independently to each of the (up *to* eight) plate edges.

The practical limitations *to the* application of the software can be stated as follows:

1. PIATE MINIMUM / MAXIMUM LENGTH

The BRITSHELL system will develop shell plates:

from 0.075 metres to 20 metres, or
from 3.0 inches to 66 feet, or
to that length which the shipbuilder or contractor can roll or form the plate.

2. PLATEHINIMUK/ MAXIMUM WIDTH

The BRITSHELL system will develop shell plates:

from 0.075 metres to 5 metres, or
from 3.0 inches to 16 feet, or

to that length which the shipbuilder or contractor can roll or form the plate.

3. PIATE THICKNESS

The BRITSHELL system will develop shell plates without any limitation to the plate thickness- Plates with a negative thickness may be specified. The algorithm first evaluates a reference surface at the mid-thickness position; this surface may be based on either frames or waterline data and is with due regard for curvature. The development is with respect to this intermediate surface.

4. MAXIMUM BACK SET

The BRITSHELL system will develop shell plates with whatever back set the shipbuilder or contractor can roll or form; from our experience this is approximately a maximum of:

- 35 mm or 1-5 inches by rolling.

However, greater values can be achieved by heat line bending.

5. MINIMUM CURVATURE IN WIDTH DIRECTION

The BRITSHELL system will develop a shell plate with whatever minimum radius of curature the shipbuilder or contractor can roll or form the plate.

6- LIMIT ON TWIST

The BRITSHELL system will-develop a shell plate with whatever twist the shipbuilder or contractor can roll or form the plate.

7. RATIO OF THICKNESS TO BACK S12P, CURVATURE, etc.

The BRITSHELL system will develop a shell plate with whatever thickness the shipbuilder-or contractor can-roll or form the plate.

8- RATIO OF BACK SET TO LENGTH

The BRITSHELL system will develop a shell plate with whatever ratio of backset to length the shipbuilder or contractor can roll or form the plate .

9. RATIO OF BACK SET TO WIDTH

The BRITSHELL system will develop a shell plate with whatever ratio of backset to width the shipbuilder or contractor can roll or form the plate.

10- RATIO OF CURVATURE TO WIDTH

The BRITSHELL system will develop a shell plate with whatever curvature ratio the shipbuilder or contractor can roll-or form the plate.

11. RATIO OF HINIMUH CURVATURE To THICKWESS

The BRITSBELL system will develop a shell plate with whatever curvature ratio the shipbuilder or contractor can roll or form the plate.

12. OTHER LIHITATIOMS

The software is designed to develop plating which is usually based on a frames definition (buttock view) of the shell. Plates can optionally be defined on waterlines and may be reflected about one edge, e.g. for soft nose stem plates. Transom plates require intermediate manipulation.

APPENDIX 10.1.3

CALI &ASSOCIATES, INC. REPORT

In order to fulfill the requirements for Phase I of the LIMITATIONS OF COMPUTERIZED LOFTING, CALI & ASSOCIATES, INC. delivers the following composition containing:

A. Description of our methodology.
B. Discussion of problems and our solutions.
C. Statement of limitations associated with our system.

A. SPADES METHODOLOGY FOR SHELL PLATE DEVELOPMENT

The methods utilized in SPADES for shell plate development are the 'Girth Length' and 'Triangulation' techniques.

A. The Girth Length method should only be used when the majority of the plate is flat and little or no double curvature exists on the curved portion. With this method, the program uses the flat portion as the development plane with all the girth computations from the flat edge towards the tangent curve. The portion of the girth falling on the-curved surface is rotated to account for the increased girth in the normal direction, leaving the flat portion undistorted. See sketches 1 & 2.

B. The commonly used method is Triangulation. The program is based on three space points to define a circle, and the girth length is calculated from the circular arc length. The degree of approximation is a function of the amount of curvature in the direction of the diagonal (true girth vs. arc girth). The program has a built-in checking routine with warning messages printed during the development, when the cross diagonal yields results with more than one sixteenth of an inch (1/16") deviation. See sketches 3 & 4.

Plate development in SPADES is performed with procedures contained in the 'Plate Development Module' and the 'Part Generation Module'.

1. The plate development module is limited to a Plate with two seams (upper and lower) and two butts which must be parallel to the plane of the frames. Plates that do not have this type of boundary configuration are developed in the part generation module.

A. <u>SPADES METHODOLOGY FOR SHELL PLATE DEVELOPMENT (continued)</u>

2. In the part generation module, boundary definition can be contours and/or butts and seams with the plate capable of being subdivided into ‘multi-parts’, each of which can be developed with the same techniques as in the Plate development module. The final development is achieved by the combination of the ‘multi-parts’.

The user chooses which method of development should be employed and the system automatically applies the development from the flat or least curved side of the surface to minimize the error propagation. The transverse contour is divided into multi-sections, up to eight (8), to get the best approximation of the diagonal girth used in triangulation.

The user has the option to override the decision made by the system in order to cross check the output of the developed parts for the compound curved - plate, by forcing the development from the opposite point in the plate. The two patterns are then compared for the amount of deviation between them.

3. Also in the part generation module,the user has the ability to manually develop the plate using triangulation techniques consisting of grid definition and manipulating the direction of the development. The technique of opposite development is also used when deemed necessary.

B. <u>SHELL DEVELOPMENT PROBLEMS AND SOLUTIONS</u>

To put the problem in the proper perspective, the obvious must be stated, i.e., <u>“Development of a compound curved surface into a flat pattern is a mathematical impossibility”.</u>

The premise is therefore that any development is an approximation and the task is essentially as follows:

A. Obtain the best possible approximation.
B. Acceptance of the approximation i. e.,

To judge whether or not the approximation is conducive to the efficient forming and fitting of the shell plate.

B. SHELL DEVELOPMENT PROBLEMS AND SOLUTIONS (continued)

A. Obtaining the best possible approximation is a function of two (2) factors:

1. Method of development.
2. Straking of surface (placement of seams and butts).

1. Method of development.

Within this context the use of a 'CAD-CAM' system is implied. It is also assumed that all available systems have techniques for obtaining a good approximation (see section I. for a description of the methodology used with 'SPADES').

2. Straking

It is assumed that in modular construction placements of erection butts is the first priority.

Seams reflecting module breaks however, are subject to possible changes due to hull form restraints.

The effect of straking plays an important role as to limiting the possibility of using the development obtained through the system.

Too often straking is done with the following order of importance:

- Pleasing appearance of seams
- Best material utilization
- Hull Form restraints

To minimize production problems this order should be reversed.

B. **SHELL DEVELOPMENT PROBLEMS AND SOLUTIONS** (continued)

- Hull Form restraints

Some of the natural hul1 restraints can be minimized by proper fairing techniques within the constraint of not altering the characteristics of the Lines. For instance, forward waterline endings (elliptical, radial, or other) shouldbe translated into a smooth (preferably straight) radius variation versus girth of stem profile. The same is applicable to curved transorns, transitions between hull and transom, and any other similar areas. This will result in longer pieces of plate and minimize the welding.

It is obvious to everybody that a chine/knuckle line dictates the need for a seam/butt. An inclined butt is also generally mandatory following a few inches after the tangent line between the hull and wrapper plate(s). Too often, however, no attention is placed on the need to locate a seam following an inflection curve in the hull if one should exist.

The amount of backset vs. plate curvature and thickness that is acceptable from a forming point of view by the shipyard should obviously be the most important criteria in straking.

Questionable areas should be developed using the system. After satisfied with Hull Form restraints then proceed to finalizing the straking using other criteria such as:

- Pleasing appearance of seams
- Best material utilization

B. SHELL DEVELOPMENT PROBLEMS AND SOLUTIONS (continued)

One of the results of proper straking techniques is also the early determination of areas where the hull form dictates the use of:

- Hot formed plate
- Plate segmentation (orange peeling)
- Castings and their extent

B. Acceptance of the approximation.

The first step is to judge the degree of approximation. The 'SPADES' user accomplishes this by the reverse development technique mentioned in the 'methodology' and by scrutinizing it very closely when alerted by the system. The amount of acceptable development deviation is a function of the plate length. There is no substitute for lofting experience and knowledge of the shipyard's capabilities in this step.

The second step concerns forming. Can the shipyard apply the correct amount of backset by cold pressing or line heat method for the given plate thickness?

Failure to meet the deviation criterium or the forming, dictate the need to add stock (excess material) on one or more edges of the plate.

If not done during the straking process, when the hull form mandates it;

- Plates will be subdivided into smaller pieces by adding butts and/or seams.
- Jig construction data will be generated for hot forming.

B. SHELL DEVELOPMENT PROBLEMS AND SOLUTIONS (continued)

In summary, problem causes ‘can be summarized as follows:

TYPE A. - System
TYPE B. - Hull Form
TYPE C. - Straking
TYPE D. - Shipyard Capabilities

In the case studies the type of problem, if any, will be explained in detail, and the recommended solution will be stated.

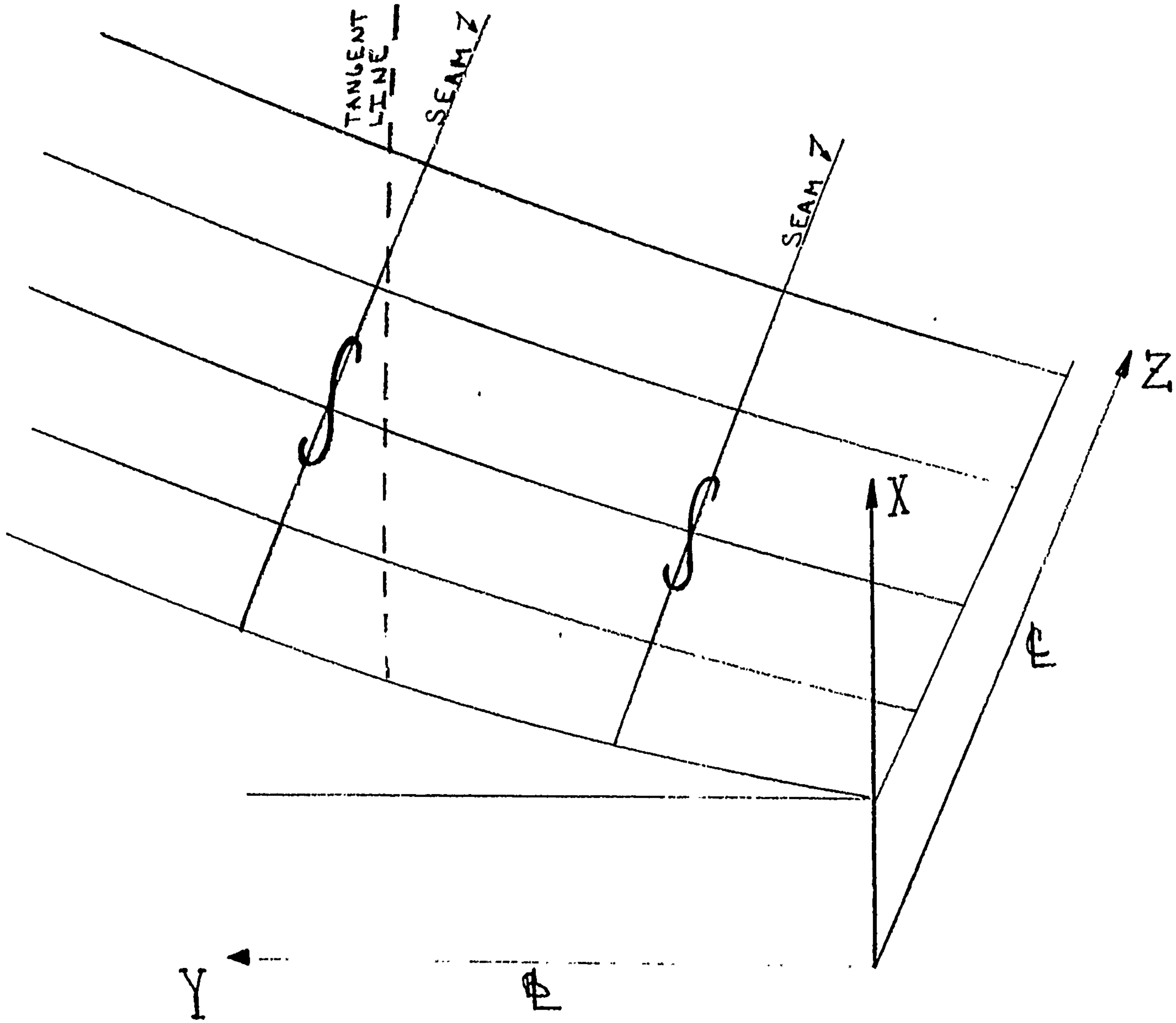
C. LIMITATIONS

It can be stated that within the ‘SPADES’ computer lofting system there are no limitations in regards to the capability of the system to obtain an approximation.

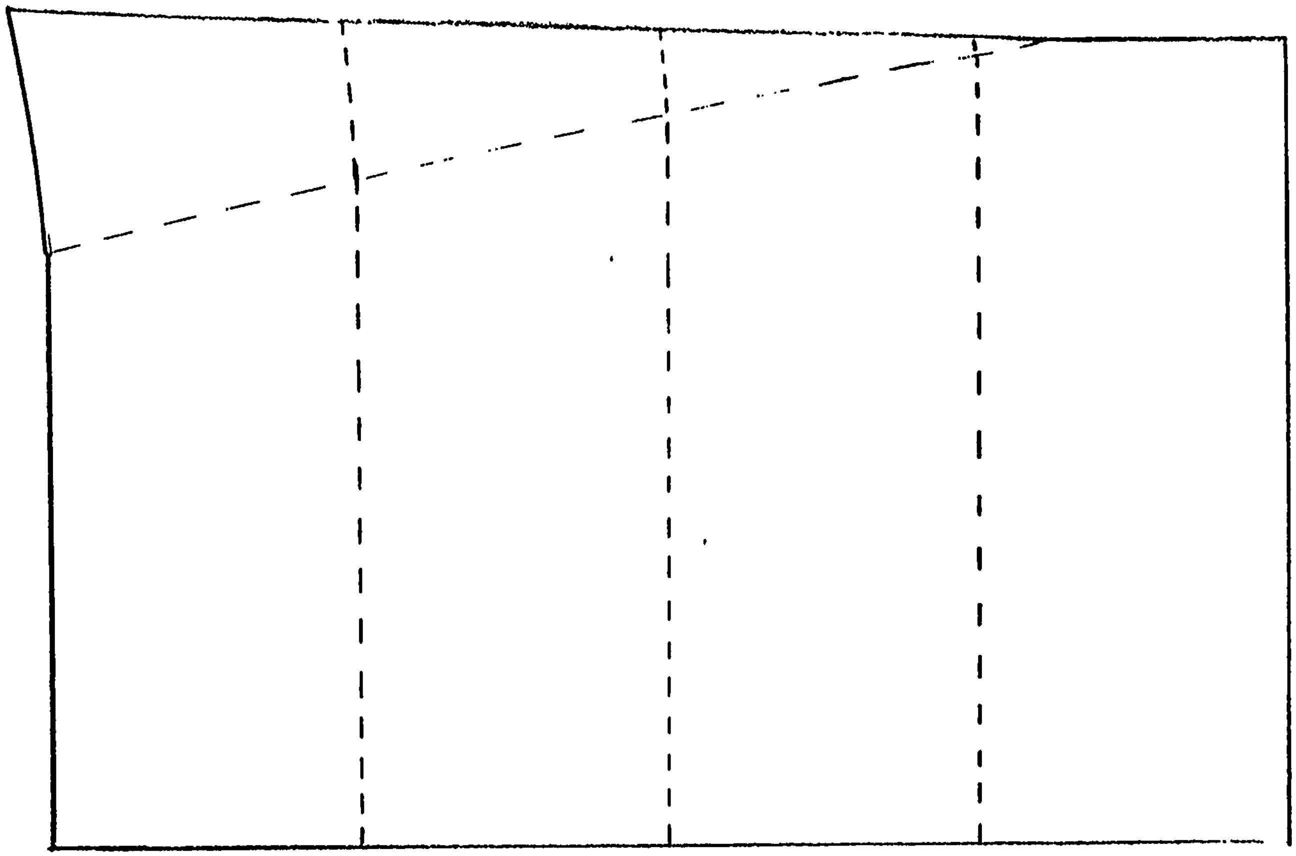
Please note that judgments and cross-checking by the user are to be stressed, not because of system limitations but for the other numerous factors mentioned in this text.

Shell plate development by any method (computerized or manual lofting) requires skilled personnel with knowledge of the shipyard’s capabilities in regards to forming and fabrication. With the ‘SPADES’ lofting system, method 1. (please refer to section A.) requires a minimum skill level while methods 2. & 3. require a highly skilled user.

SKETCH 1

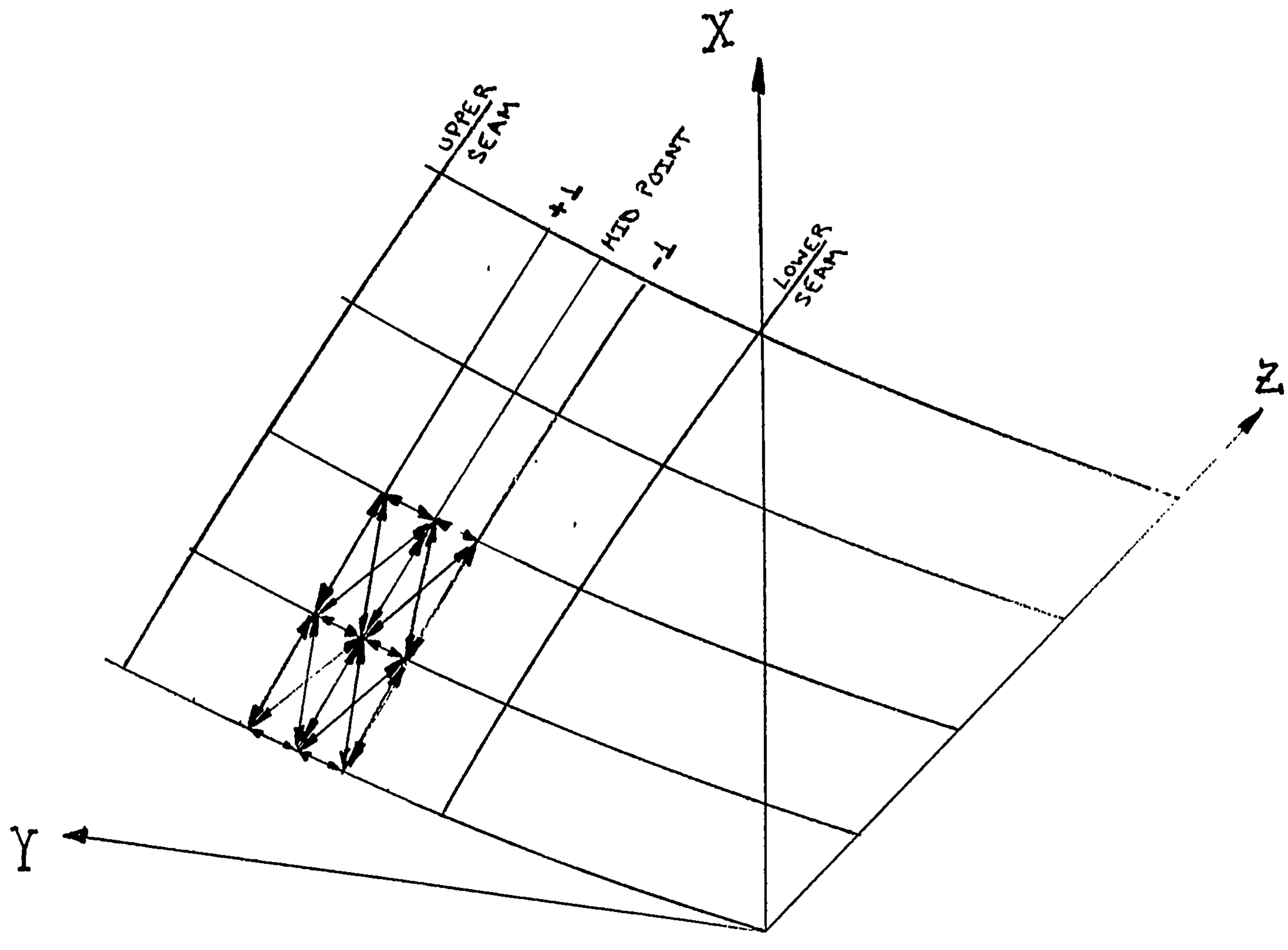


SKETCH 2

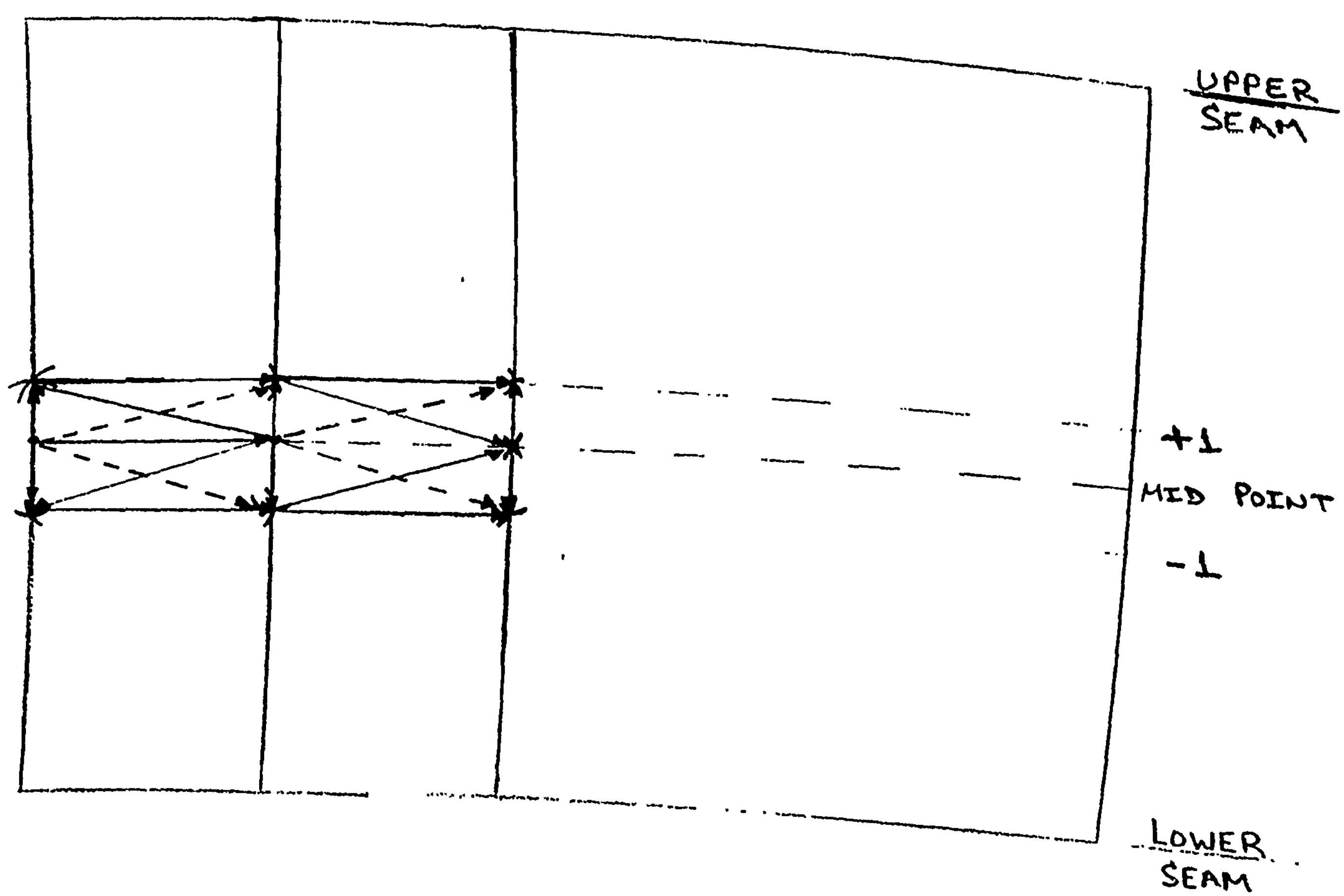


DEVELOPMENT

SKETCH 3



SKETCH 4



———→ = GIRTH USED FOR DEVELOPING

- - - - - -→ = DIAGONAL GIRTH USED FOR CHECKING

DEVELOPMENT

APPENDIX 10.1.4

COASTDESIGN, INC. REPORT

A) Description of methods used for shell development

Coastdesign Inc. has produced the AutoPlex and AutoPlate programs to be used for the purpose of shell development.

<u>AutoPlex</u>

The program AutoPlex must be used at the design stage to generate a hull which may be plated by pure bending, no stretching or thinning is required in order to form the resulting plates. The resulting hull surface is said to be developable.

<u>AutoPlate</u>

The AutoPlate program method provides for plates to be expanded on any shape of hull and takes into account the strain required to form the plate. The term compound curved is used to describe these types of surfaces which cannot be formed purely by bending. The amount of compound curvature is measurable as gaussian curvature.

The geometry of the hull for use in AutoPlate is provided by a hull design and fairing program called AutoShip. AutoShip can either be used to create a hull design or to match the geometry of an existing hul

Description of methods used by AutoPlex

AutoPlex is used for hull design and plate expansion of developable surface hulls. This software is used at the design stage since developability is an inherent property of the shape of a hull. A surface which is developable is one which can be formed by pure bending. An example of this is a cylindrical or cone shape. A developable surface is highly preferred as a plateable surface since no plastic deformation of the shell plating material is required. This eliminates the need for some types of compounding equipment such as spherical dies. A developable hull may be plated by pulling the plating material over frames, although more commonly, some rolling or bending equipment is required. The AutoPlex software has made it possible to design hull shapes which were previously thought to be too complex to be developable. Within AutoPlex, the sheer, chines and fairbody are defined by as mathematical splines of the general form Y=fn(X) and Z=fn(X). These splines define the boundaries of panels which run the length of the hull.

AutoPlex searches adjacent chines for ruling lines. A ruling line is an axis of bending. Mathematically it is a straight line connecting the two boundary curves and is defined by a plane that is tangent to the hull surface at every point on that line. Depending upon the resolution a user selects, AutoPlex finds 20 to 1000 ruling lines on each panel. See Figure 1

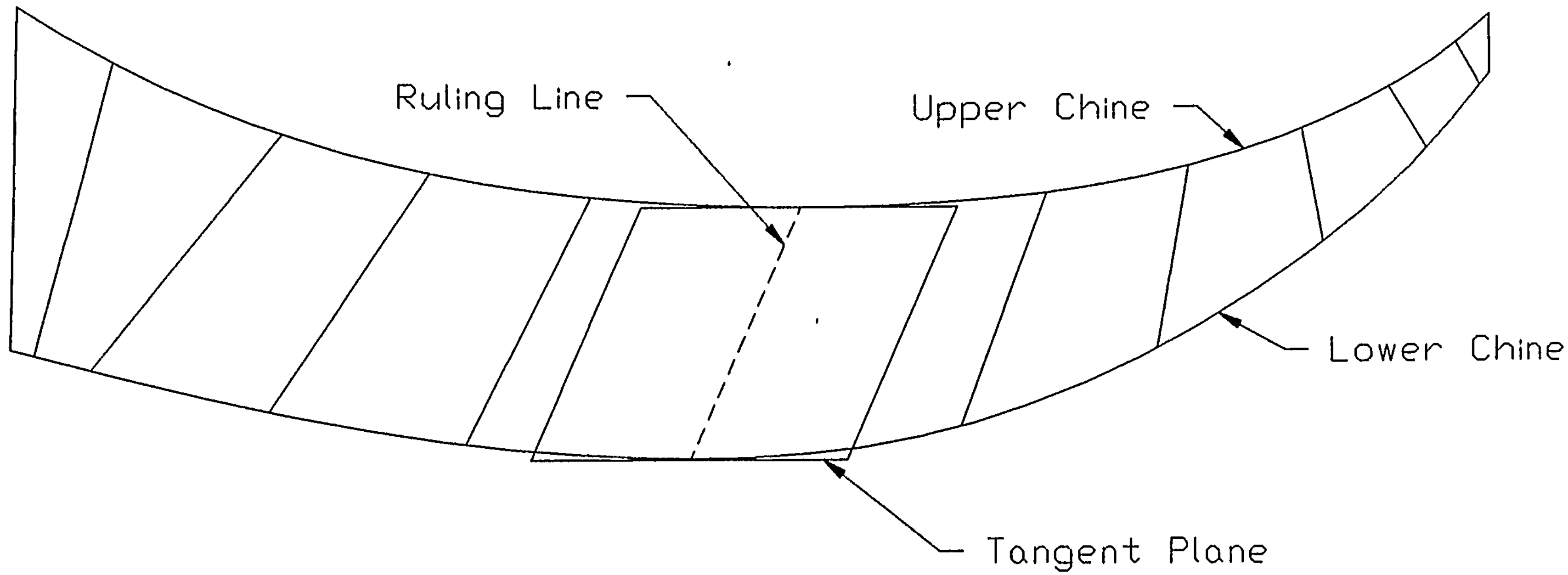


Fig. 1

We have proven that a developable surface will always exist between any 2 chines and as far as we know, Autoplex is the only program capable of always finding a developable surface between chines. Some systems will fail to find a developable surface in flat areas or areas with pronounced twist. In the event of an unsatisfactory resulting sectional shape, the user must edit the master cumes to refair the chines. Generally if the chines are fair, and adjacent chines are of similar character, the hull will develop well first time.

A developable surface is very different from a ruled surface. The “ruling lines” on a ruled surface neglects the need for mutual tangency at the chines and connect the chines in an arbitrary manner. Only by a rare coincidence would a ruled surface be a developable surface and therefore the advantages of exact plate expansions and plate formation by pure bending no longer exist.

Once the ruling lines have been found between chines, the panels may be expanded. The chines and ruling lines form the boundaries of a series of facets. These facets are always planar. The facets are continuous and can be laid out side by side in the 2 dimensional plane to produce a file representing the plate outline. Most commonly a plate outline file is written in a CAD format for further processing or N.C. cutting. Stations, waterlines, buttocks, intersections with any plane and ruling lines can all be mapped onto the plate outline file. Figures 2 and 3 show a hull surface designed in AutoPlex and the resulting plate expansion. Ruling lines, stations, buttocks and waterlines are mapped onto the expanded plate.

Hull Lines Developed in AutoPlex

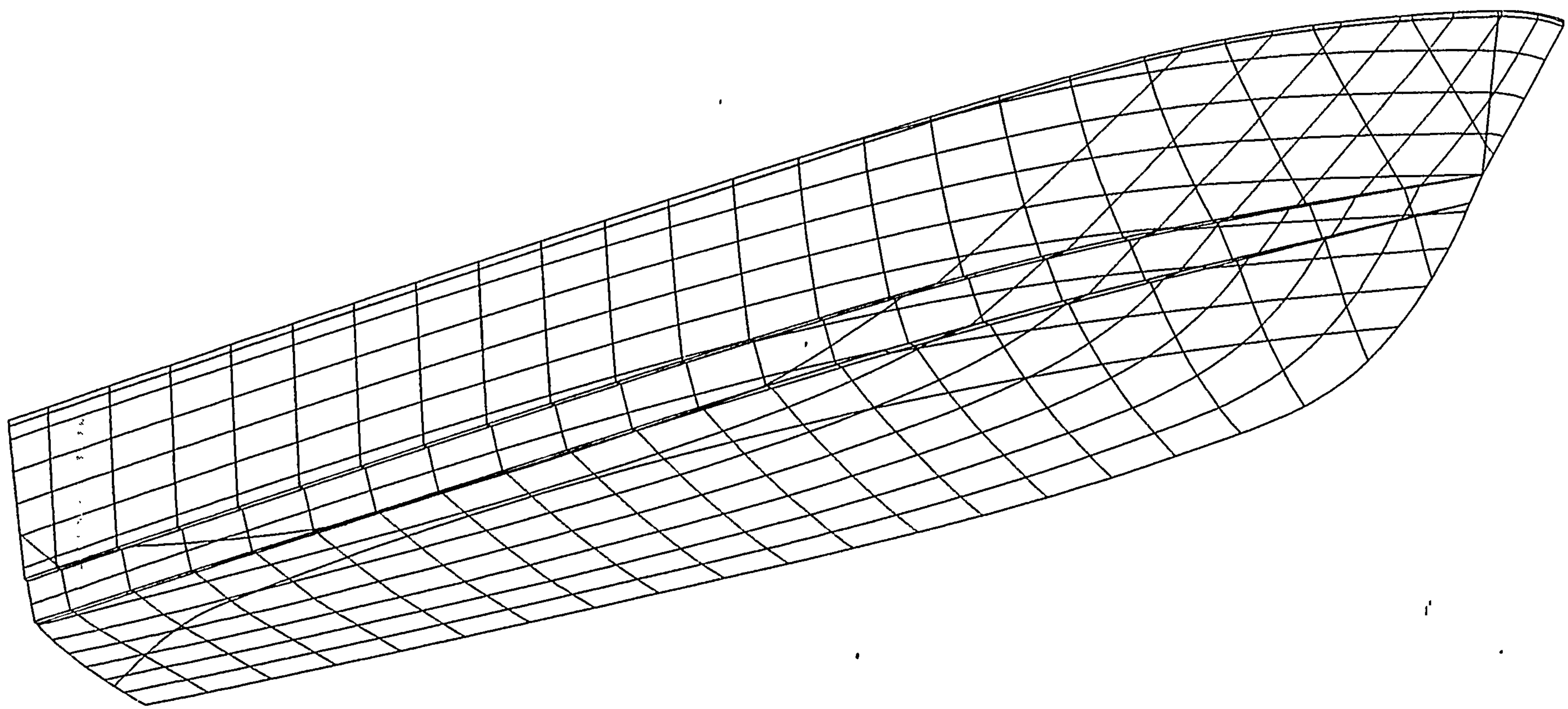


Fig. 3

Plate Expansions From AutoPlex

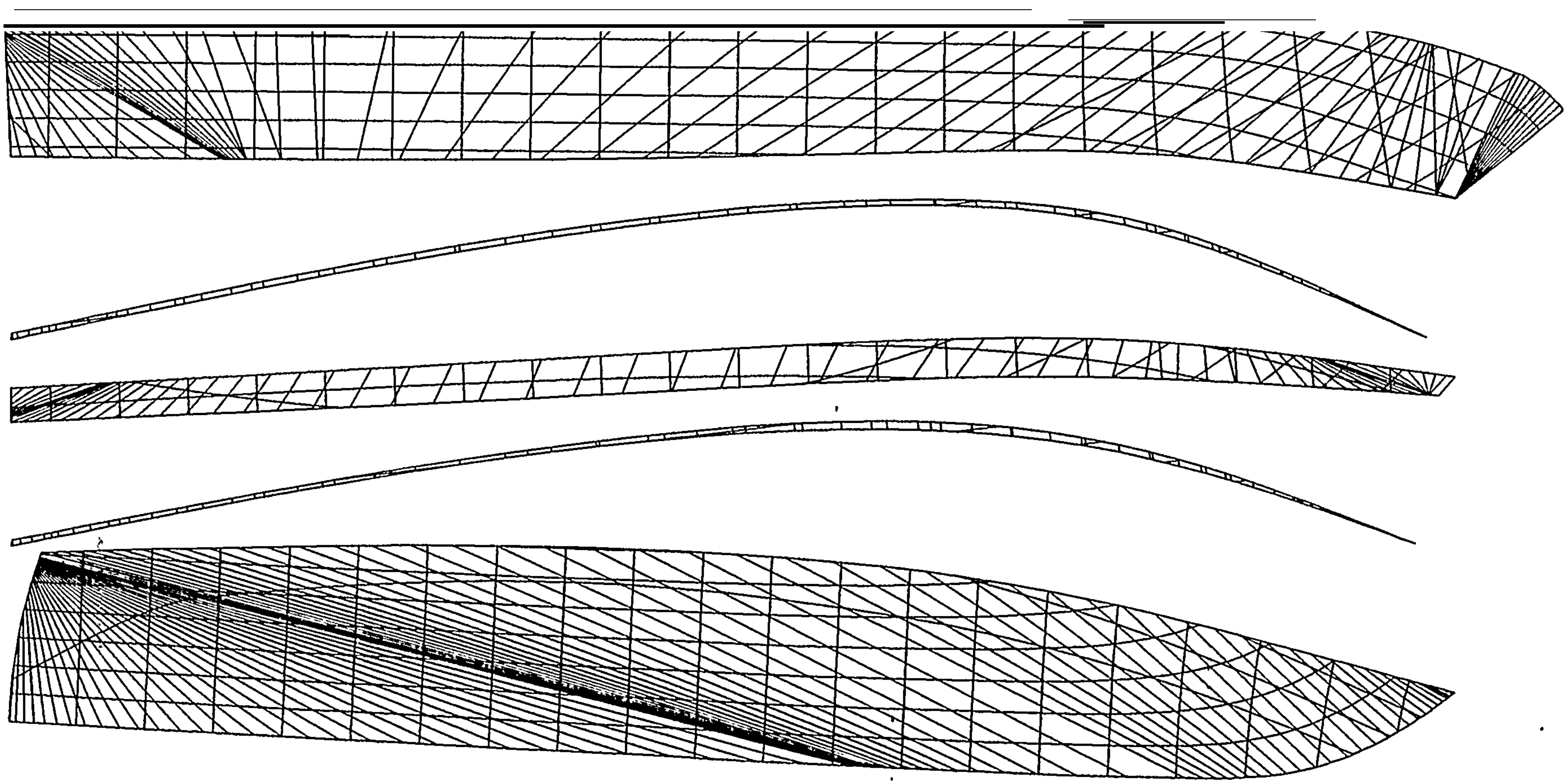


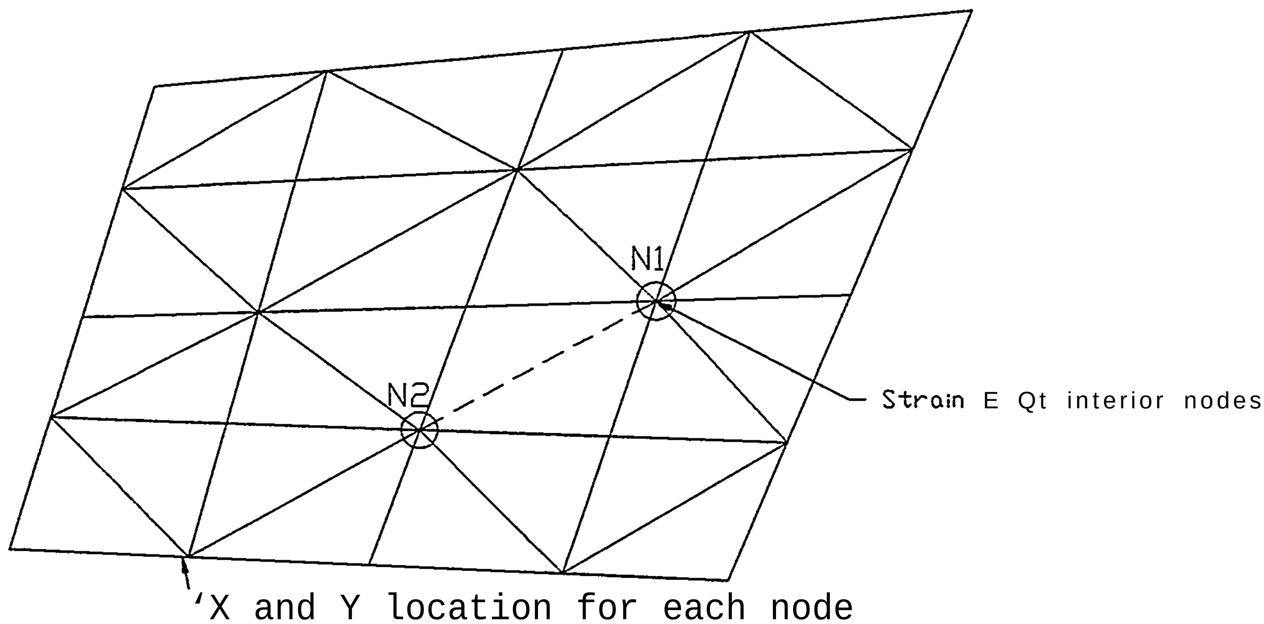
Fig. 4

of methods used by AutoPlate

The Autoplate program is used for expanding plates which have compound curvature. This type of hull is sometimes called a round bilge hull, however this is not accurate since a developable hull may also have a round bilge.

Autoplate uses a representation of the hull geometry from the AutoShip program. The AutoShip program represents surfaces as first, second or third order b-splines in the transverse direction and cubic polynomial splines in the longitudinal direction. Hull geometry may be matched to an existing lines plan by use of a digitizer. Offsets from an offset table may be entered as an aid to define hull geometry.

AutoPlate expands a patch on the hull by a finite element method. The patch is represented by a series of points or nodes on the hull surface. The length of geodesic paths are measured between adjacent nodes. These geodesic lengths are later used to define the relative positions of nodes in the 2 dimensional case. Since the surface patch may have compound curvature, the link lengths (geodesic distances) must be altered slightly in the 2 dimensional case. The factor by which the link lengths must be changed is equivalent to the strain required to form the 3-dimensional surface from the 2 dimensional starting blank A large number of simultaneous equations must be solved in order to arrive at the nodal positions with their associated strains.
Avery cursory description of the mathematics is included as figure 2. This method of plate expansion is protected by U.S. patent laws. It is used by Coastdesign under licence from AeroHydro Inc..



25 Nodal Locations * 2 dimensions = 50 unknowns
Unknown Strain for 9 interior nodes = 9 unknowns
Total of 59 unknowns

Link Equation
(XN1 – XN2)^2 + (YN1 - YN2)^2 = G^2 * ((EN1 - EN2)/2)^2
EN1 = Strain at N1
G = Geodesic length between N1 and N2

One link equation for each link = 56 equations
Fix X and Y for one point = 2 equations
Fix Y for 1 point = 1 equation
Total of 59 equations
Number of equations = Number of Unknowns

Fig.. 2

B) Description of known shell plate probiems and how these problems are taken care of.

The idea of developability is important in the understanding of limitations of AutoPlate and AutoPlex. Generally speaking the limitations inherent in AutoPlex are related to the hull shape whereas limitations in AutoPlate are related to the forming process.

It is possible to use both AutoPlex and AutoShip to define different parts of the same hull. By using both programs the area of compound curvature can be limited to a small part of the hull. An example of where this is useful is on a hull with a flared bow with parallel sections running aft such as a planing hull. The flared bow sections can be designed in AutoShip so that these plates can be expanded in AutoPlate. The rest of the hull can be designed and expanded in AutoPlex.

AutoPlex Problems

In using AutoPlex, the designer has complete control over the shape of the sheer line, the chines and the fairbody line which form the boundaries of a panel. A designer has no control over the shape of the sections between these boundaries because it is a function of the developable surface. Fortunately, the sectional shapes are usually very close to the intended sectional shapes.

Shipyards cannot use Autoplex to define a plate to match an existing hull unless the part of the hull is known to be developable or unless the existing shape can be altered. The hull lines from AutoPlex and the lines of the existing surface can be compared in order to determine the amount of discrepancy. This is easily done in a CAD program or by comparison of offset tables.

A potential problem exists in AutoPlex on hulls with straight, non parallel chines. The true developable surface which exists between these boundaries must have a diagonal kink across this panel. Often the kink will be insignificant, but the resulting hull lines should be examined carefully to ensure fairness. The resulting kink can usually be reduced or eliminated by putting some slight curvature in the splines representing the chines.

AutoPlex assumes zero shell thickness. On a hull with thick plating it may be necessary to reduce or expand the hull lines by 1/2 of the amount of the plating thickness in order to compensate for this. Reducing or enlarging the hull geometry is a very simple task in AutoPlex.

The fairness between chines is checked by examination of the resulting hull lines in AutoPlex. Obvious unfairness in the hull lines can usually be seen on the computer screen, however the lines should be plotted and examined carefully to ensure a fair hull.

AutoPlate Problems

The expansion of compound plates could be made exact using a finite element method, if the strain could be imposed on the plate exactly as specified. The value of strain cannot be measured or generated with sufficient accuracy for this to occur. Many methods do not explicitly account for strain induced in the metal during forming which allows the finite element method to be somewhat more accurate. The compounding process is very gradual and the operator is unable to measure or recreate the strain imposed on the plate directly. A great deal of skill is therefore required. The operator must also use tools which do not necessarily cause equal strain in all directions such as roller planishing or line heating.

The strains which arise from the compounding process and the transfer from the starting 2 dimensional plate outline and the 3 dimensional finished plate necessarily require a quantity of excess material around the edges of the plate outline which will later be removed as waste. In addition, the edge material acts as a restrain to compound forming.

A good 2 dimensional starting plate outline will assist the operator and decrease the amount of excess material, however some excess material will nearly always be required. Actual plate expansions on an icebreaker hull which were performed by Polar Design Associates indicate that the worst circumstance requires the addition of 1/2″ of excess material on an 8′ X 20′ plate. A letter written by Polar Design is included in this report to support this claim.

POLAR DESIGN ASSOCIATES LTD
630 Millbank, Vancouver, B.C., Canada V5Z 4B7 Phone (604)873-4601, Fax (604)874-2735

Gunnar Solheim
COASTDESIGN NORWAY
Solsiden 1,
N-4950 RISOR

NORWAY

January 1.0, 19

RE: AUTOPLATE Software

Dear Sir,

I refer to your fax of January 04, 1991, in which you have requested our comments on the new Autoplate software.

Under the agreement with CoastDesign Inc. we have been testing the software for the nine months on the 300 ft ice breaking research vessel, presently under construction at North American Shipbuilding Inc, in Louisiana, USA. At the time of this writing some 50% of the plates developed with Autoplate are installed, with the rest being at various stages of NC cutting, forming, etc. The fol owing is the summary of our comments and conclusions with regard to suitability the software for shipbuilding.

The hull form was designed for minimizing the areas of compound curvature, which account for some 30% of total shell area. Consequently, most of the compound curvatu are quite extreme. The remaining 70% is either flat or developable surfaces, the later developed with the aid of Autoplex software with satisfactory resu lts.

The Autoplate has been used to expand Al compound curvature areas. The present test release has produced outlines of expanded plates with frames, decks, etc. mapped thereon (strain map is optional). For the purpose of forming the plates, which has been subcontracted to the Avondale shipyard in New Orleans, L.A for each individual plate have Men indicating the main axis of rolling and providing a set of templates based frame lines generated in AutoShip. When formed and installed, the largest discrepancy reported did not exceed 1/2'' *or* 12mxn on a 8ft x 20ft plate, which is reportedly best shipyard ever handled and in fact may be attributed in part to the hull distortion.

The seams have been laid out by the yard in an arbitrary manner, generally following waterlines, rather than generated automatically from Autup]ate.

The software itself, although offering tremendous time and savingsrequires significant experience with preparation of the database, running and interpreting the results. In particular, definition of the edges must be based on sound experience and interpretation of the local form in order to avoid repetitive work, Following our feedback, we understand some of these tasks will be made automatic in the upcoming release. T output in the form of a 13XF file definitely. requires a fair deal of processing in AutoCad before it is ready for NC cutting. We are willing to offer further advice on the subject.

in short, the software reduces manhours to estimated 10% of those needed for manual development, produces accurate results thus eliminating a need for marglns, on site lofting and trimming, etc., but requires a lot of experience with using it in practise.

Yours Sincerely
POLAR DESIGN ASSOCIATES LTD.

Peter van Diepen

CC/COAST DESIGN INC., SURREY, BC

It is usually necessary to export the plate drawing to a CAD program such as AutoCAD in order to finish the plate expansion drawings in their final useable form. Some of the reasons for this need for extra processing are listed below.

-Currently, there is no way of automatically adding excess material to the plate outline.

-There is no means of automatically dimensioning the plate outline.

-There is no way within AutoPlate to fit a spline in order to smooth the edges of the plate outline.

-There are no provisions for text such as title blocks

It is possible to automate these processes by means of using lisp routines within AutoCAD as has been done by Polar Design Associates of Vancouver.

The current version of AutoPlate does not have the ability to generate templates for use in checking the shape of a plate. This is an important feature which will be incorporated into anew version of AutoP1ate which is under development. The present solution for defiiing these templates involves expordng the hull lines into a CAD program and measuring offsets in the area of the plate on stations buttocks or waterlines. These offsets are used as a basis for drawing templates.

Occasionally AutoPlate fails to converge on a solution to the complex set of simultaneous equations. This is a very rare occurrence but code is built into the program to expand these plates by a method of triangularization. By this triangularization method, geodesic distances are calculated along 3 connecting points on a 3 dimensional surface. Distances are then used to construct a 2 dimensional triangle. All of the triangles are assembled together into a 2 dimensional triangle to make them fit into a continuous shape. The difference between this method and the finite element method is that the resulting change in distances or geodesic path length is taken explicitly into account and distributed evenly in a radial pattern about the center of maximum strain. There triangularization method is therefore less accurate but provides a backup method when the finite element method fails.

Both AutoPlex and AutoPlate assume zero thickness. On a hull with thick plating it may be necessary to reduce or expand the hull lines by 1/2 of the amount of the plating thickness in order to compensate for the plating thickness. Reducing or enlarging the hull geometry is a very simple task in the AutoShip and AutoP1ex programs.

C) Limitations of AutoPlex and AutoPlate

AutoPl limitations

Since AutoPlex is both a hull design tool and a plate expansion program, problems with difilcult shell expansions are avoided by constraining the shape of the hull surface. The limitations are therefore mostly limitations on the possible shapes which can be modelled. Some specific examples are listed below.

Flared bow

One of the inherent attributes of developability is that since the chines and sheer line are convex in plan view, the shape of the sections between the chines must also be convex in body view. A flared bow by definition requires concave sections between the sheerline and chine and therefore this type of bow cannot be modelIed.

Straight Frames

A developable surface with straight sections is only possible if there is no twist in a panel. A panel with no twist is one which has parallel sections. It is possible to develop simple hulls with this constraint but it is too restrictive in most instances.

Bulbous Bows

A bow which has smooth circular sections cannot be incorporated in a hull shape in AutoPlex since the only possible developable surface for this shape is either a cone or cylinder.

Away of proving intuitively that these shapes are not developable is that they are impossible to model with a flat sheet of paper. For example, a smooth bulbous bow cannot be a developable surface for the same reasons that a piece of paper cannot be wrapped around an orange.

The inability to model and thereby expand the shell plating for these shapes can be solved by modelling these shapes in AutoShip and expanding them in AutoPlate. Unfortunately, the advantages of developability are lost.

There are also some cases where a developable surface cannot currently be modelled by AutoPIex. A limiting factor in the present version is that ruling lines cannot run longitudinally such as might be desired for a submarine with a parallel midbody and cylindrical sections.

The plates which are defined in AutoPlex cannot be made to cross chines. The chine forms a plate boundary and the plate is trimmed to this chine.

AutoPlate Limitations

Any deformation of the surface by pure bending alone does not result in a change of the Gaussian curvature. The resulting output therefore does not contain any bending information such as rolling axis but only compounding information in the form of strain. A system has yet to be devised in AutoPlate which will give the main axis of rolling.

A plate with more than 4 sides cannot be defined in AutoPlate. It is possible to reduce a plate with mom than 4 sides into more than one plate, however the resulting plate expansions must be cut and formed as they are defined in AutoPlate. The plate expansions for a developable surface can be split up or reassembled, but such is not the case with an AutoPlate generated plate expansion.

The actual plate expansion requires many complex calculations which require a great deal of time compared to most triangularization methods. Within AutoPlate, it is possible to define all of the plate boundaries and then perform all of the expansions at once. Roughly 10 minutes is required to expand a single plate at maximum resolution on a 33 MHZ, 486 computer. The program can be left to run overnight if necessary.

APPENDIX 10.1.5

KOCKUMS COMPUTER SYSTEMS AB REPORT

Limitations of Computerized Lofting, Phase 1

RNy / Stee 920406

l.l Shell Plate Development Description

1.1.1 The Hull, brief information.

The AUTOKON 3D model is built up by sculptured and planar surfaces. All curves describing the hull of a ship or floating structures are stored in the sculptured surface. Forreasons not to be discussed here, AUTOKON has built up its hull by curves represented by geometry stored in a database. We are NOT using any surface algorithm to generate curves. Curves are given interactively by the user using crosshair points, 3D input point or point(s) picked from other curves. The system will on command from the user generate a serie of curves in any projection. A fairing algorithm, KURGLA, fairs the curve in very much the same way as a good old wooden spline.
See enclosure 5 for a picture of a hull on database.
There is no known limitation Elated to the shape of the hull. Normal production fairing time is 40 to 120 hrs.

1.1.2 Shell Plate Development

1.1.2.1 User Definition

Shell plates are defined using the same set of commands as for defining plane parts. Commands for adding thickness, excess, shrinkage or other auxilary functions are available. The user can choose from crosshair pointing on plate comers or interactively typing the limiting seam curves' names. A shellplate can have a maximum of 99 limiting seams. This means the shellplates can have maximum 99 comers.
Marking curves are stored according to user given options. Internal structures as bulkheads etc. limited by the shell, will from now on consider the plate thickness. See enclosure 1. The shellplate can be symmetrical, non symmetrical or crossing centerline. See enclosure 2.
Commands are available to calculate the unexpanded plates' attributes such as area weight and centre of gravity in ship coordinates.
Jigg and templates are calculated on user request These calculations can be carried out even though the plates are not defined or developed.

1.1.2.2 User Expansion of shellplate

When the plate has been described, the user can tell the system to expand the plate. The system can develop the plates using longitudinal, transverse, or lateral curves, by user option. There is one single command for the expansion of the plate. Rolling lines are automatically calculate& for the present only the main rolling direction is shown. When an expanded plate is shown graphically the first time, the expansion grid is shown. The plate can be shown expanded or not expanded with or without thickness. Commands m available to calculate the expanded plates attributes (considering excess etc.) such as area and weight.

1.12.3 The Development Method

Each plate is expanded on a more or less rectangular grid. The geometry of expansion curves are taken from the model, which is stored in the database so no time is used to regenerate any expansion curve. Expansion curves can be tranverse frames, water lines or buttocks. The grid is defined by these expansion curves. Using the outer contour of the part, the program selects a subset of expansion curves, and then a certain piece of each curve. The arc of this piece (called expansion curve) is divided into 4 to 20 pieces giving 5 to 21 XYZ points on each curve. The spacing between pairs of expansion curves is then developed by triangulation, giving U-V coordinates, and the patches thus formed are nested together in a plane. During the triangulation the system uses true girth along expansion curves and circular interpolation between curves in the other direction, not just straight lines between points.
XYZ points are 3D points in ship coordinates. W points are 2D local points for an object, here the expanded plate. Now we have a XYZ grid and an UVgrid. The program computes a set of Coon’s patches for the XYZ grid. The result is a mapping from XYZ to W for the plate. Therefore, for every point on the outer contour and the marking curves the program can find the W-point from the XYZ coordinates. Such point sets are found for all curves on the plate, and finally planar curves are faired through the point sets, giving us the geometry of the expanded part. See enclosure 3.
The system calculates a basis line for the expansion. This line crosses all the expansion curves. The system starts the triangulation and nesting from this curve and works outwards down on pairs of expansion curves. During the nesting process of the expanded patches the system find out where and how much stretch or compression the plate has.

1.1.2.4 'Classical' vs. 'Special' plates.

The system generates the expansion grid in two very different ways that the user should know about, since it affects the way plates should be treated in the problem areas.
A 'Classical' plate has 4 edges. TWo edges are on expansion curves, i.e. butts, and the other two are the classicalticaluppermdlowm-.Forsucha plate, the system selects the expansion curves between the butts, and uses the arcs of these curves between lower and upper seam. This is enough to get a good grid system and a correct development.

If one of these requirements is not filled i.e. not 4 edges, not 2 butts, the system needs to find an extra expansion curve outside each end of the plate. The curve arcs are selected by cutting the curves against a rectangle in the projection of the expansion curves, e.g. the bodyplan.
In addition, the user can tell the system to treat some curves as limitation curves for the grid i.e. treat the expansion grid as if these curves were knuckle curves (chines). The rectangle will then be limited by these knuckle curves. See enclosure 4.

1.2 Known Problem Discussion

1.2.1 General

As for old fashioned shell plate development computerized development has its problem areas. Since AUTOKON is fully interactive the user has several ways around problems. The hull should be quite well faired with goal definition of areas with much curvature and seams and butts (butts are seam curves in AUTOKON) loaded with development of difficult areas in mind.
See enclosure 5 for a picture of a few seams on a hull.

IE.: Seams and butts are loaded according to unit breakdowns. Seams within the unit sometimes have to be moved by the lofting people as plates in bulb areas are often expanded better if seams are loaded as perpendicular as possible to expansion citrves.

There usually are about two to three plates on some hulls that we do not deliver as developed shell plates, due to several mixed factors.

In addition to the measures mentioned below, the user can control the plate development by

- Choosing the number of subdivisions on the expansion curves
- Loading extra expansion curves
- Setting expansion grid limits via ‘knuckle curve’ option

1.2.2 Shell Plate at Knuckle Curves (Chines)

The AUTOKON system has no problems with knuckle curves on the shell surface.
Sometimes one or more limiting seams on apart are knuckles. Since the system may choose an expansion grid that extends outside the part (for non-’classical’ plates), the user has to take certain extra steps when knuckles limits the plate. The user must telI the system that the curve should be treated as a knuckle curve, although the system does know that

this curve gives knuckle points to all intersecting curves. When we have toId the expansion module that the curve is a knuckle curve, the grid will not be extended outside the plate, and we will have no problems with the discontinuity of the curvature at the knuckle.

1.23 Lower-, Upper-, Forward-, and Aftmost Shell Plate

Shellplates located in the extreme parts of the ship very often cause problems for computerized development The users of the AUTOKON system have to take certain steps in these areas. If the plates can be defined as 'classical' plates them is no problem.

1.23.1 Lowermost Shell Plate

Let us call the plate limited by or crossing the symmetry line the lowermost plate. A typical example here is a keel plate or a soft nose plate. Since the AUTOKON system can handle port-, starboard and nonsymmetric parts this does not cause the user any problems. The only extra step the user must take when plates cross centerline is to make sum that the symmetry plane includes the centerline, that is, during the fairing process one particular curve is named the symmetry curve for the shell.

1.23.2 Uppermost Shell Plate

The AUTOKON system has no problems with the uppermost row of shellplates as long as there are expansion curves forward and aft of the shellplates, and the expansion curves are set to be YZ-curves (transverse curves). If (for some reasons) the expansion curves is set to. be X'Y-curves (waterlines), the user must load a waterline above the upper extreme of the hull. This is no problem since the plate definition and hullfairing are modules within the same prograrn. There must be at least one expansion curve outside the shellplate on each side, unless the butts are expansion curves and there are exactly 2 seams in addition to the two butts.

1.2.3.3 Foremost Shell Plate

The foremost shellplate can be the nose plate in a bulb. We do not recommend the users to expand this plate using the shellplate development build into the system. It can be done, but the result is unreliable. We recommend the built-in macro language, the users should write a macro developing such plate using principles from developing parts of spheres. However, we are now in the process of refining our methods of plate developing. This will result in safer development of such nose plates.

If the plate is the upper and foremost plate in the bow, the user has several options. In this area the hull has lots of shape and it is important that the user define a few extra expansion curves. The expansion will not be accurate if there is too much slope between the expansion curves. Closer definition of the expansion curves may be necessary. In the bow, the user can define XZ-curves (buttock lines) as expausion curves. As a side effect of the refining now being done, the system can warn the user of areas that need more expansion curves.

1.2.3.4 Aftmost Shell Plate

The aftmost plate very often ends at transom. If expansion curves is YZ-curves this causes a problem. The user then tries XY-curves. Again if expansion curves outside the plate is missing the user can generate these. If the plate cannot be made as a classical plate, a dummy tie (straight vertical line in the center plane) can be used to satisfy the requirement for extra expansion curves.

1.2.4 Plates partially in plan bottom plan side

Plates located partially in plan bottom or plan side is a common problem area. The system has to make sure that the development process does not "twist" the plate in the flat area. We have no existing reports that this causes any problem for the AUTOKON shell plate development.

1.25 Miscellaneous plates

A plate located in the upper portion of the bulb and the lower portion of the bow (saddle plate) is a problem if the plate is too big. The system will expand the plate, but it may be very hard to manufacture the plate. We recommend that the user break the plate down into smallerpieces if necessary, but first try closer expansion curves if the first development is not acceptable.

In general plates with very much shape can cause problems for both development and manufacturing. Even though it seems that the AUTOKON development process gives an acceptable result we often advise the user to break the plate down into smaller pieces and load more expansion curves. This will make the life easier for the manufacturing department.

Plates in sonardomes and bulbs has to be defined with care. This plate can cause problems if defined too big. The user has to break the plates down into smaller pieces if allowed Extra expansion curves has to be loaded The AUTOKON system has good experience with expanding shellplates in sonardomes on US and Canadian built navy vessels.

1.3 Practical Limitation Discussion

The known limitations are:

Max plate dimension ca32000mm (length and width) due to nesting. Otherwise AUTOKON have no other physical limitations for shellplates.

Min 2, max 100 expansion curves

Min 4, max **21 subdivisions of each curve.**

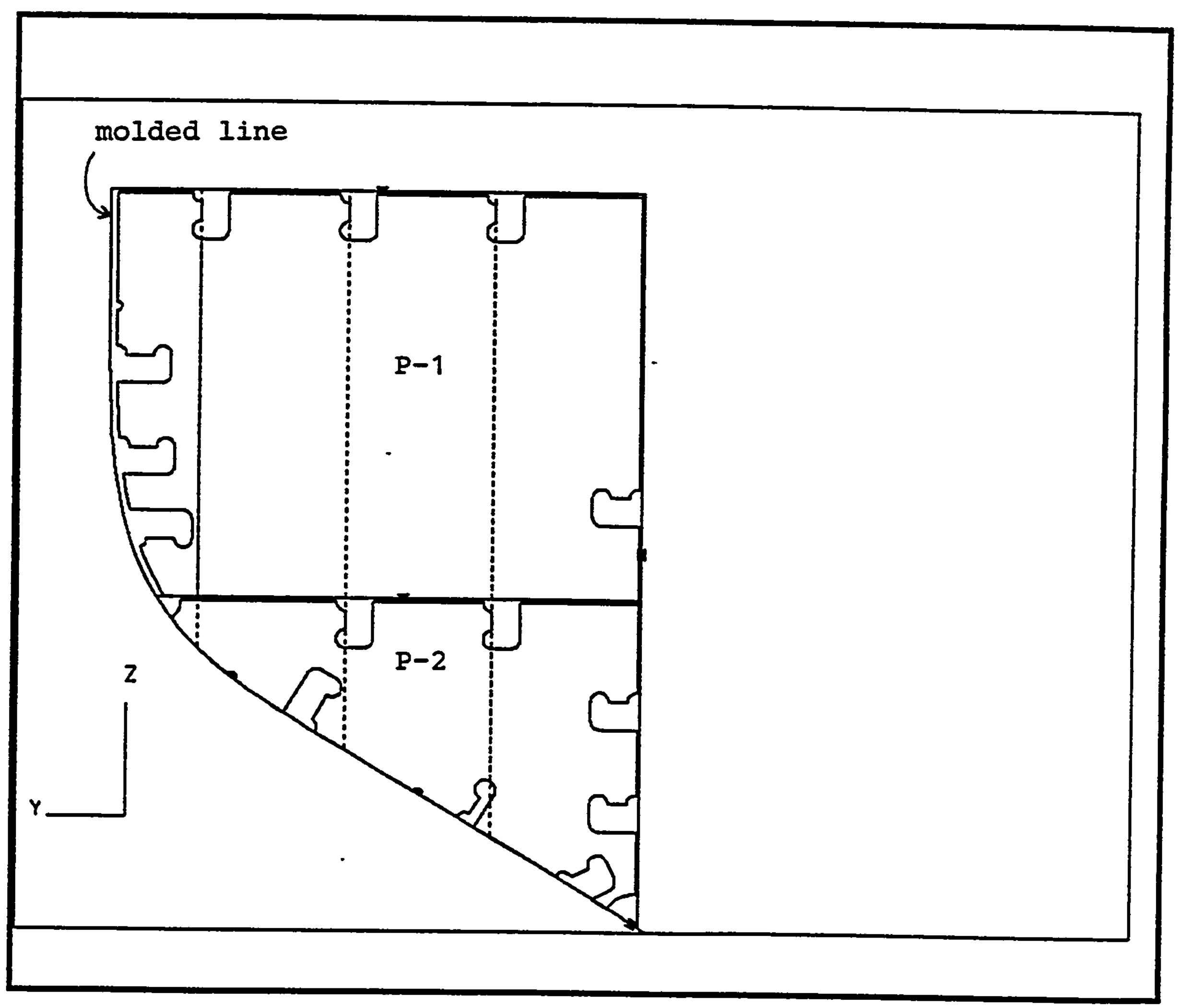
We are currently exploring the limits of accuracy, with a view to giving the user information about plateslams that need special attention.

Othervise, any plate that can be fabricated can also be developed

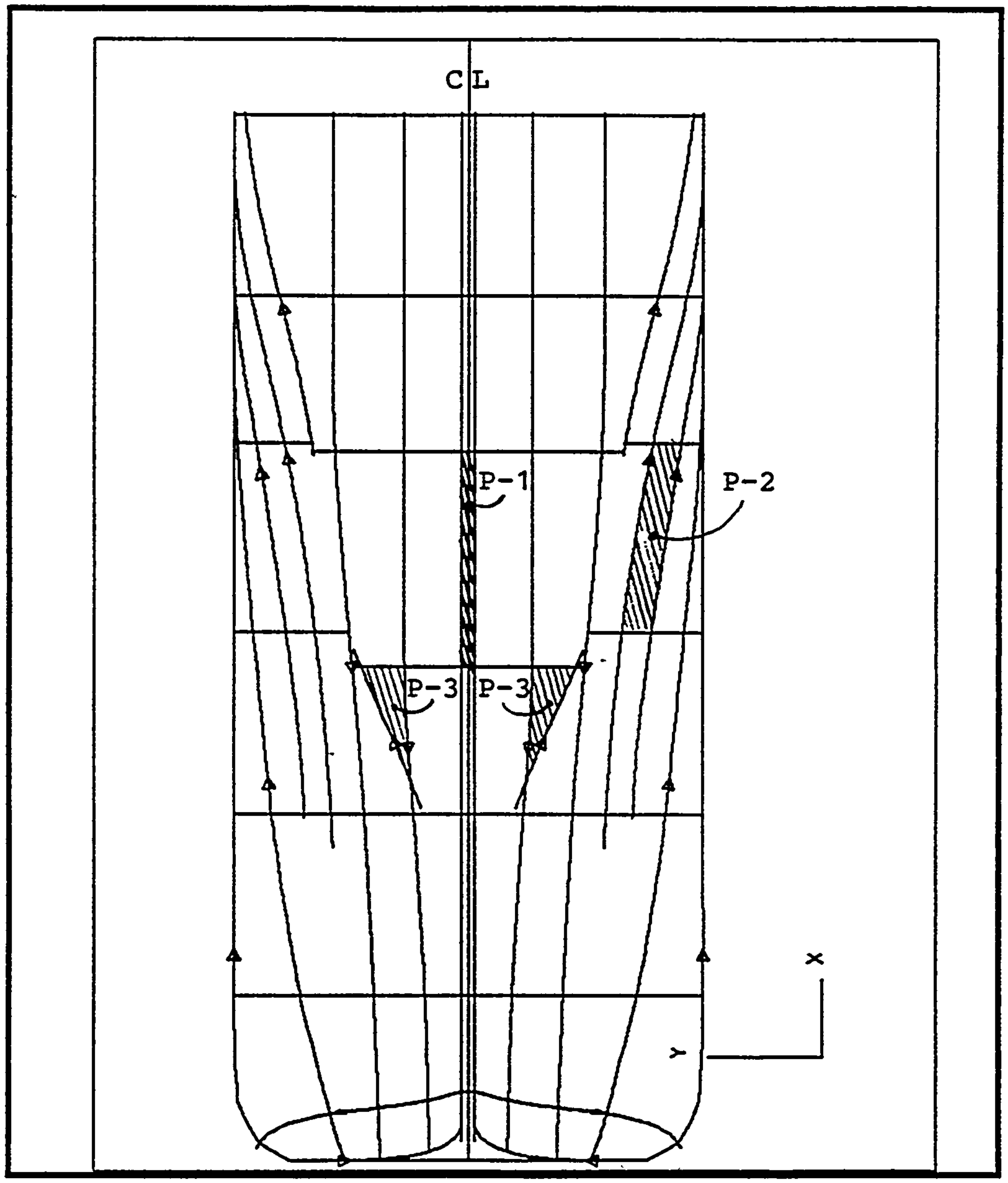
Internal part, limited by shell

P-1 adjusted for shell plate thickness

P-2 not adjusted for shell plate thickness



Symmetrical, non symmetrical parts

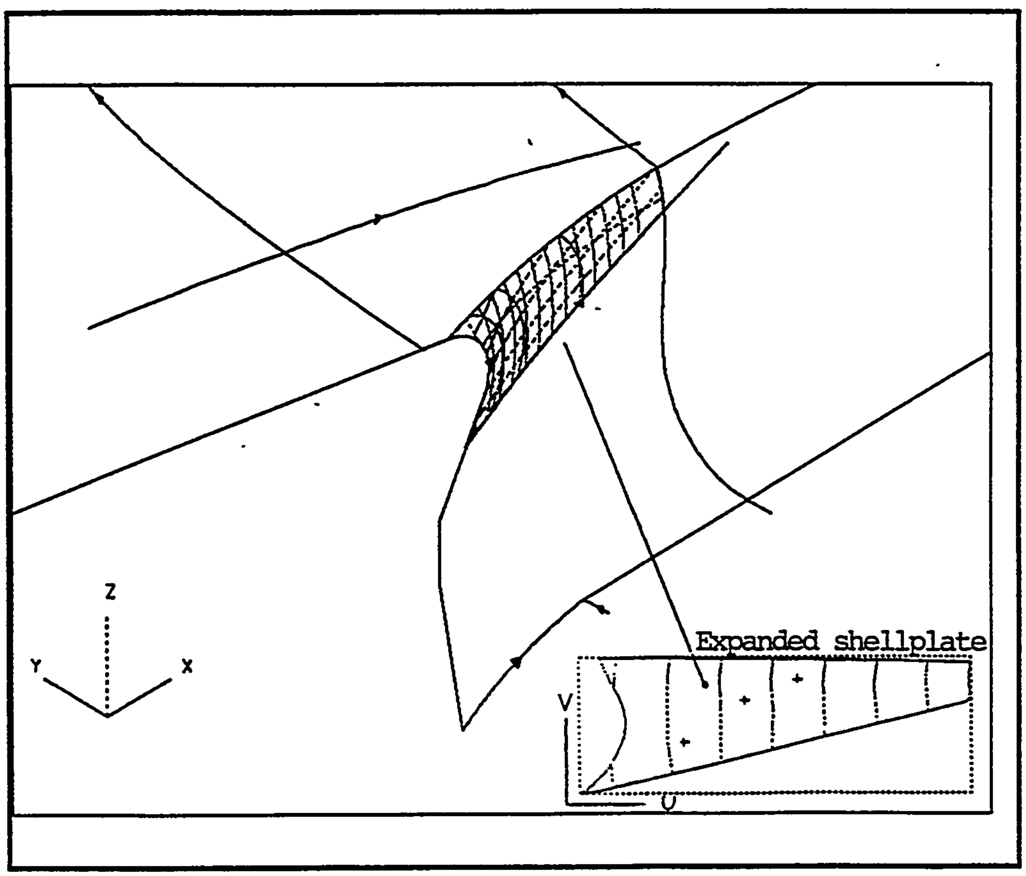


P-1: Part defined as non symmetrical, in this case crossing centerline.

P-2: Part defined only with "starboard symmetry".

P-3: Part defined with "both symmetry".

Detail of hull, seams and shellplate shown

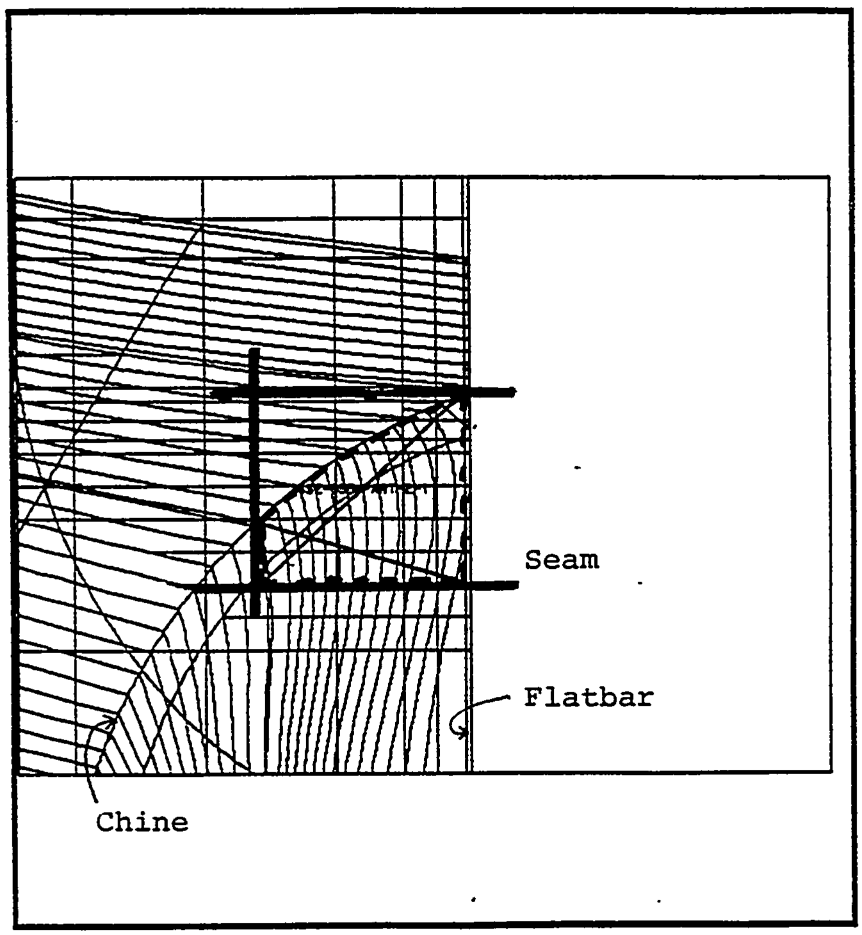


X : Longitudinal

Y : Transverse

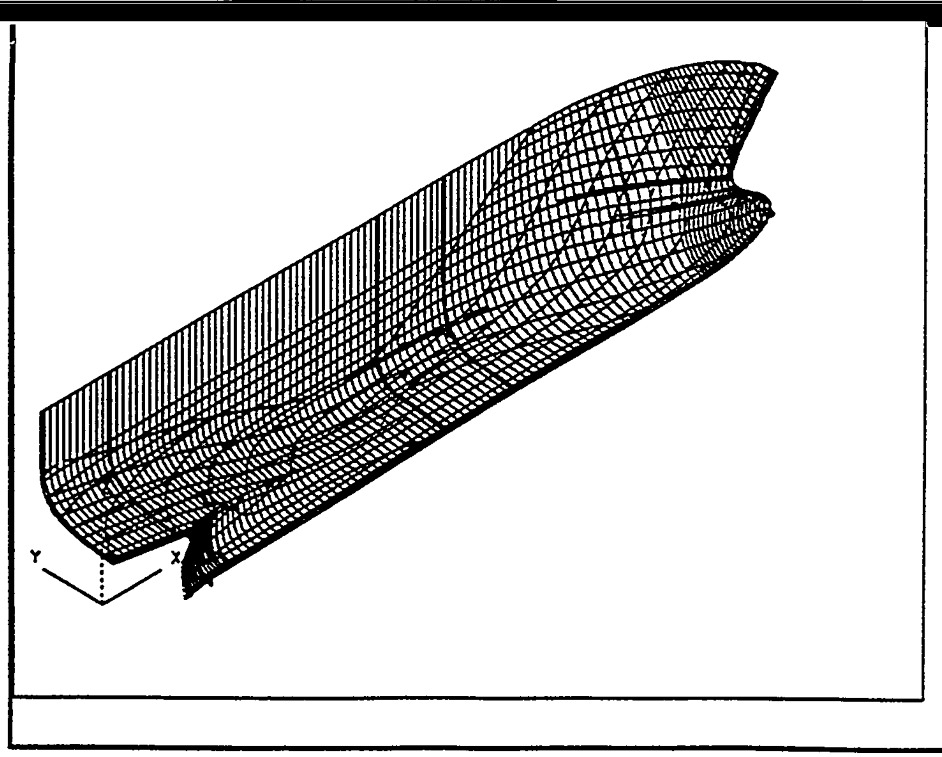
Z : Vertical

Detail of hull showing all curves in end view

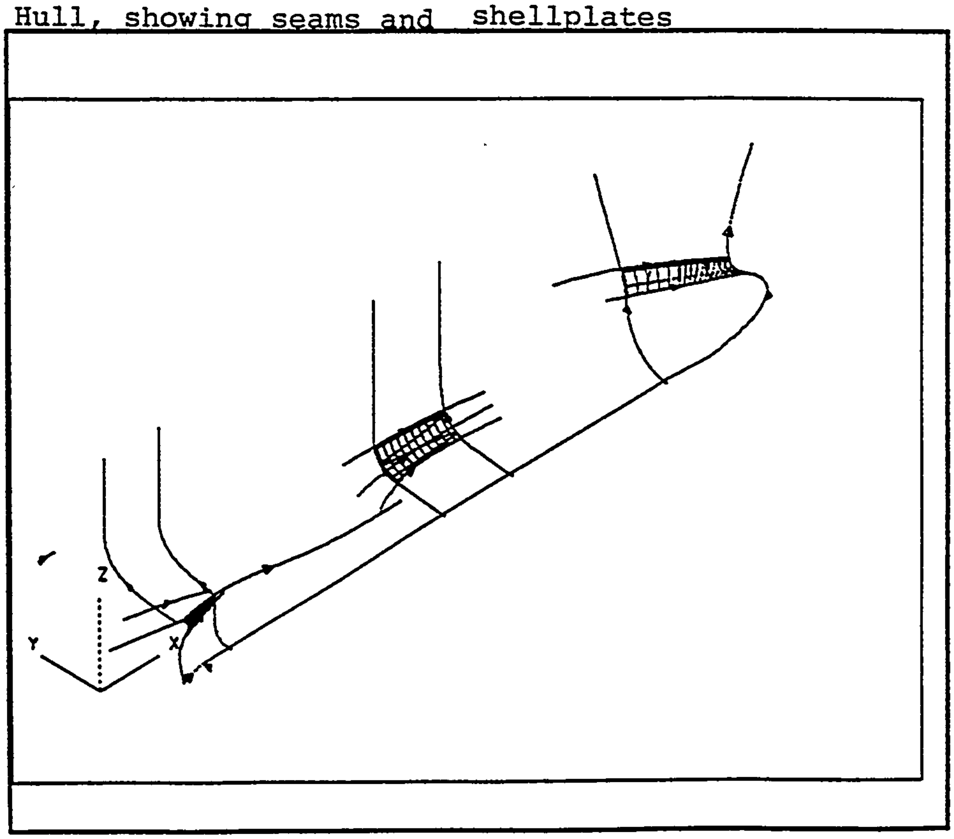


End view, part in aftbody against stern, with a hard chine as upper seam.

The circumscribing rectangle shown in this view will cut out the frames used for development unless the upper seam is declared as knuckle.



Hull, showing seams and shellplates



APPENDIX 10.1.6

SENERMAR REPORT

SHELL PLATE DEVELOPMENT METHOD USED IN FORAN SYSTEM

1.- INTRODUCTION

The main object of this task is the rational definition of shell plating taking into account the common thickness zones, the construction method and the shipyard resources and standardization..

We started from the fact that the hull surface of the ship is, mathematically speaking, undevelopable then we decided to transform the real surface into a developable analytical surface within each plate. Under FORAN System the problem of developing the shell plates is not based on the existing approximate methods for calculating the true distance measurements. Instead of this, from the begining of the process, the non-developable real surface of the hull is substituted by a set of analytical developable surfaces within each plate.

This method has been in practical use since 1972.

2.- GENERAL DESCRIPTION

The shell development algorithm is based on a substitution of the hull surface of the ship around the zone of a shell plate by the most adjusted mathematically developable surfaces (cylinders and/or cones). The only practical limitation of the algorithm is that the surface of the hull, inside a shell plate, has to be continuous or, in other words, a shell plate must not have knuckles inside (normally, knuckles are edges of the plate).

To obtain a higher precision each plate is internally broken down into mathematical domains. This breaking down is carried out automatically and for each domain the adjusted surface parameters are calculated. Then, plate development is obtained as the addition of consecutive domains. By these means the shell plates are dealt with in the same way, as they are actually dealt within the workshops, where press machines and bending rolls are used to form the plates.

As a result of the shell development process, cutting, marking and bending information is obtained as well as some useful values to help in elaborating **the plate like, developability index,** minimum length of the bending machine, main generatrix position, information for checking both bending and cutting, etc.

3.- DEFINITION PROCESS OF A SHELL PLATE

A shell plate is an area of the hull of the ship limited by four lines. The two more or less transverse limes will be named as butts and the other two, more or less longitudinal, as seams.

Thus the shell plating module is functionally divided into a number of tasks each with a dedicated aim:

- BUTT task : To define the position of the butts as well as points on butts to be used in the seam's definition tasks.
- SEAM task : To define the shell seams.
- PANEL task: To define construction shell panels
- PLATE task: To break down a shell panel into plates.

All these tasks work i.n interactive graphic way and their results are stored in a common data base to be used further on.

It is only necessary to indicate the construction frame number and a distance forward or aft the frame to create a transverse butt .

The definition of a non-transverse butt or a seam by the user is made by selecting a set of points (at least two) by indicating any pair of coordinates (the third coordinate is automatically calculated) and a condition that determines the form of the resulting line, such as:

- Parallel or pseudo-parallel to any deck, knuckle, seam, shell longitudinal and, in general, to any previously defined line.
- Parallel to one of the main axes of the ship.
- A general line defined by biarcs passing through the selected points.

This means, from the point of view of the practical use, that there are no limitations related to the seams and butts definition and to the number of knuckle points on these lines.

A.shell panel is defined by the user byselecting”graphically the four lines limiting the panel and some general attributes like panel margins, key of symmetry and assembly/subassembly block assigned to the panel.

And , finally, in the shell plate definition process the user indicates the lower and upper seams of the plates, the thickness and steel quality, and, optionally the shrinkage factors to be considered when developing the plate.

As a result of the shell plate creation the program develops the part, calculates the minimum rectangle circumscribing the developed contour and assigns, automatically, the gross plate that produces minimum scrap according to the platess catalogue of the shipyard. If the result is not the one the user expects, he has the possibility of changing the topological definition of seams and butts and recalculating the plate in order to reduce the scrap percentage.

4.- DETAILS OF TEE ALGORITHM USED

Steps followed in the surface adjustment process, is now described.

- Reading from database the topological definition of the seams and butts limiting the plate.

  Checking the position of the plate with respect to the declared flat areas of the ship (flat of bottom and flat of side tangency lines and parallel body).

- The curved plates located near the flat of bottom will be rotated 90 degrees to avoid high values in derivatives DYZ that may produce precision problems in the adjustment process. All remaining calculations are made internally in double precision.

  Calculation of a net of 65 points, saving the three coordinates and the two derivatives in the directions YX and YZ. These 65 points will be situated in 13 pseudo transverse lines and in 5 pseudo longitudinal lines. Fig. 1

- This net of points will be completely inside of the plate in the case of seams or butts coincident with knuckles; otherwise the points can be reasonably out of the plate to assure the continuity with contiguous plates. (In case of seams coincident with knuckles the use of points out of the plate would have produced bad results because the surface out of the plate may be very different from the one we want to develop due to the knuckle). The above mentioned 65 points are calculated with respect to the neutral axis of the plate (mid-thickness surface) because it is assumed that the forms of the hull represent the moulded surface.

Calculation of the plane tangent to the surface in the middle of the plate and translation of both point coordinates and derivatives 'to a new system of reference in this central point.

Checking the possibility to adjust cylinder(s) with axes perpendicular to one of the main axes of the ship. Then, cylindrical plates can be easily developed.

Calculation of the vertex of a cone adjusted to the central region of the plate with the condition of minimum value for the function:

$$\sum_{i=1}^{i=NP} (YP_i - Y_i)^2$$

(YP are the halfbreadths on the cone and Y are the halfbreadths on the real surface).

Breaking down of the plate into two conic surfaces, each of them with minimum error and having a common generatrix. This is necessary to be able to develop both surfaces without cutting the plate (continuity condition). Fig. 3

Up to now the common generatrix is passing through the central point but now we are going to move the generatrix on a projecting plane by a simultaneous adjustment of the two surfaces (domains).

Translation of the vertexes of each domain if they are inside the plate, and calculation of the real length of the basic generatrix.

Calculation of the necessary parameters to develop the plate. Calculation and evaluation of the mean square error and deviations between both real and adjusted surfaces.

At this point, it is decided, accordinq to the deviations and mean square error, if the result is good enough. If the value of the Gaussian curvature within the plate is greater than a predetermined value the plate would redivided internally into an odd number of regions (mathematical domains) for which the process is repeated from the 65 points calculation. Fig. 2

It is important to note that all mentioned evaluations and decisions are internally taken, without any indication from the user because the boundary values to take the decission of repeating the process have been adjusted after 20 years of experience and hundreds of ships developed with this algorithm.

Ounce the adjusted surfaces are good enough, the plate is developed by using a function having as input the three coordinates of a point on the hull and as output the two coordinates on the developed plate and using internally the parameters of the mathematically developable adjusted surfaces. It is inside this function where the shrinkage factors are applied (if defined by the user).

The total computer time for the developed process can last between 5 and 15 seconds depending on the difficulty of the plate. Then these response times make possible to include the developed process as a task of an interactive module.

5.- OUTPUT RESULTS FOR A SHELL PLATE

As mentioned before it is obtained information for steel order, cutting, marking and bending.

For steel ordering the following data are supplied:

- Number of gross plates.
- Length, width, thickness and steel quality of the gross plates.
- Gross and net weights.

Scrap percentage.

For cutting the plate it can be obtained NC information or a drawing for optical cutting and the following statistics and checking information:

- Lengths of the four edges of the plate.
- Lengths of the straight edges.
- Lengths of the curve edges.

Lengths of the plate diagonals.

- A flag indicating if the plate can be cutted or not in a parallel edges cutting machine.
- Necessary time for cutting and marking the plate.

The bending information consists of a set of transverse and longitudinal templates on the position selected by the user. This information can be numerical, graphical or for NC cutting of the templates.

Under this chapter is also obtained the following information:

- Warping (developability) index of the plate.

- A flag indicating if the plate is flat, single or double curvature.

- Minimum length of the roll press machine for bending the plate.

- Lengths of chords and diagonals of the plate for checking the bending.

All marking information is automatically calculated and it is represented in both NC and plate drawing but, optionally, the user can obtain also numerical information for manual marking. The marking contour of a shell plate can contain the following elements:

- Construction and intermediate frames.
  Shell longitudinal parts.
  Decks and bulkheads.
- Margin lines.
- Templates position.
- Bending line (generatrix)
- Any kind of reference lines at any position (for checking the assembly/erection processes).

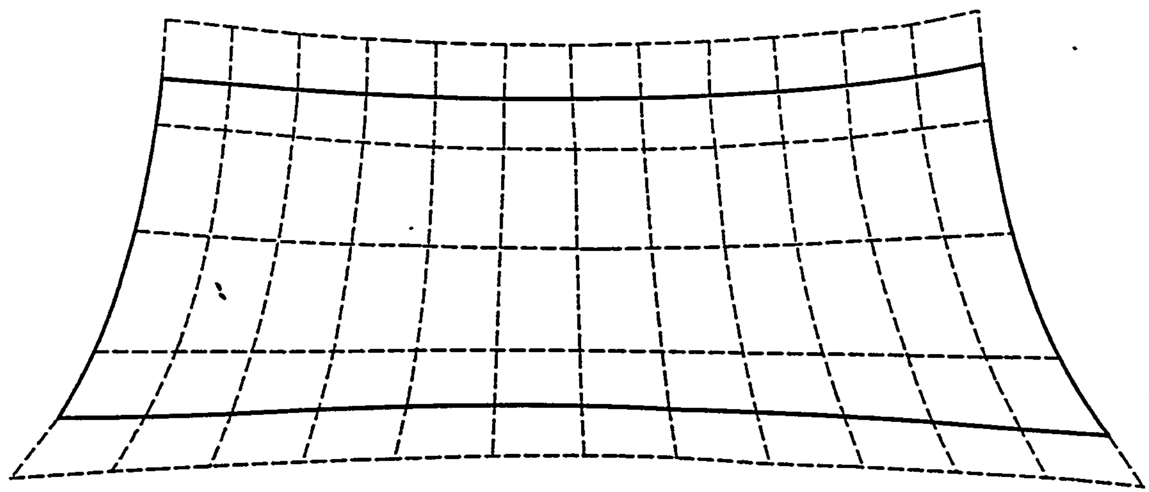


FIG. 1. SHELL PLATE DIVISION

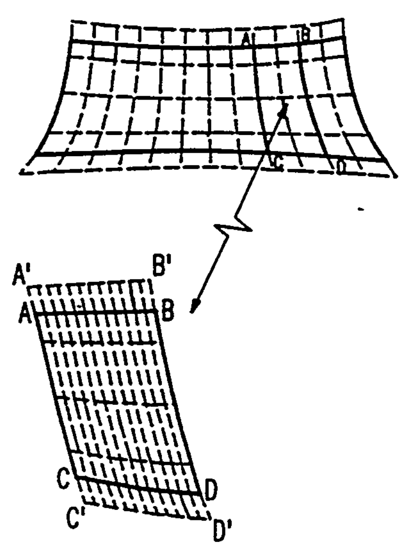


FIG. 2. SELECTED REGION

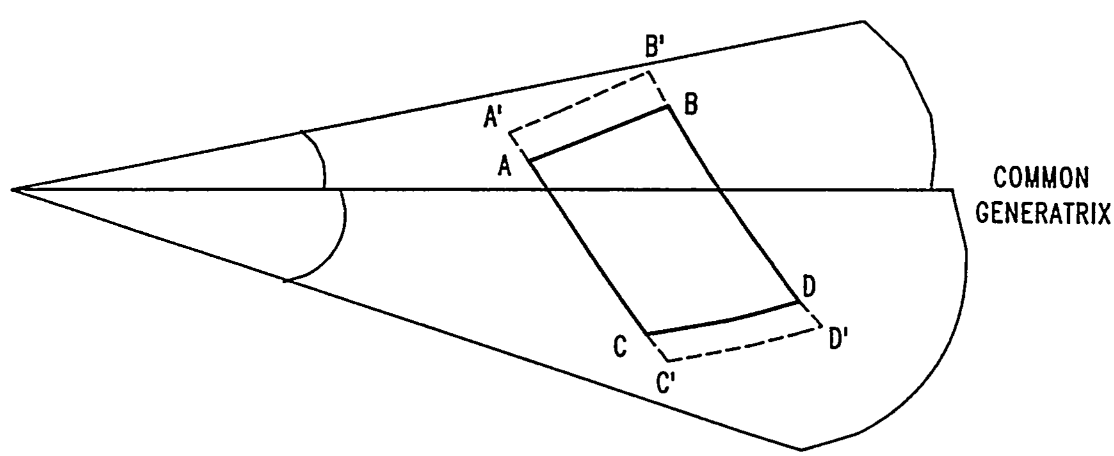


FIG. 3. 2 CONES ADJUSTED TO SELECTED REGION

TASK B.- BRIEF DESCRIPTION OF KNOWN SHELL PLATE DEVELOPMENT PROBLEMS

B.1. FORMING/BENDING PLATE

One of the main problems of shell plate development is to verify the appropriated bending or forming (in the rolling cylinder or press machine) of the plate. Different procedures for verifying the final plate are available depending on the shipyard. FORAN System can-produce different outputs:

l.- Some transversal templates and a longitudinal template are required. Verification consists to check that the upper edges of all templates (normally wooden templates) are in a plan (See fig. B.I).

2.- A device like the figures, with 1 frame and 7 sliding bars, is used in at least 3 ship frames. verification consists to check that the central bar of all devices is on a straightline (See fig. B.2)

B.2.- EXCESS STOCK OR GREEN MATERIAL

Normally green material or excess stock is defined mainly to compensate the shrinkage. In FORAN System this problem can be handled in two different ways, independently or simultaneously.

l.- To add a constant increment (it.: 50 mm, 2") in any of edges of the plate.

2.- To use an shrinkage factor in x-direction and/or Y-direction (they can be different) and automatically all coordinates of the developed plate are multiplied for the corresponding factor.

TASK C. - SHELL DEVELOPMENT PRACTICAL LIMITATIONS

There are two practical limitations:

1.- A limitation in FORAN System are surfaces close to a sphere of small radius (R).

It means R_1/R#l with RI very small, or R_1/R2~-l too.

This problem only appears at bulbous bow and the solution is to reduce the size of part by diving in two parts.

2.- The other limitation is concerning the angle between extreme transversal tangents, this angle has to be smaller than 90Q. If it is bigger, the solution is to divide the plate in two parts by adding an intermediate seam, later the two parts are nested together without cutting the added seam.

Other limitations such as: maximum and minimum length and width, plate thickness, maximum back set, etc. (as listed in your report of Nov. 21, 1991) are not concerning FORAN System. Of course, they are practical limitations of the shipyard, that are included in the definition of shipyard standard methods (Module F09 of FORAN) including maximum weight of a plate. A ‘Swarning message~i is prompted when over passing above figures.

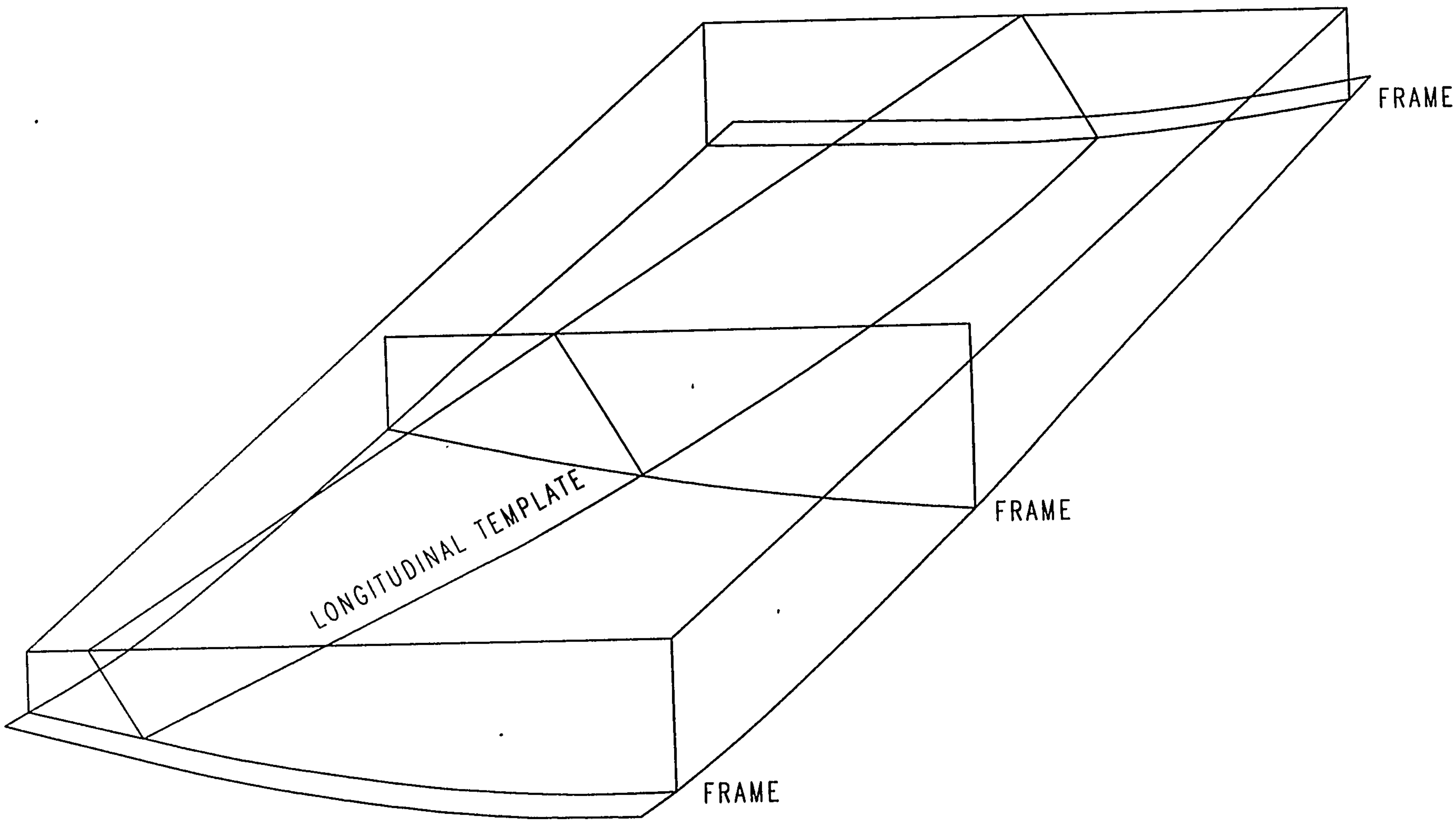


FIG. B.1 **WOODEN TEMPLATES**

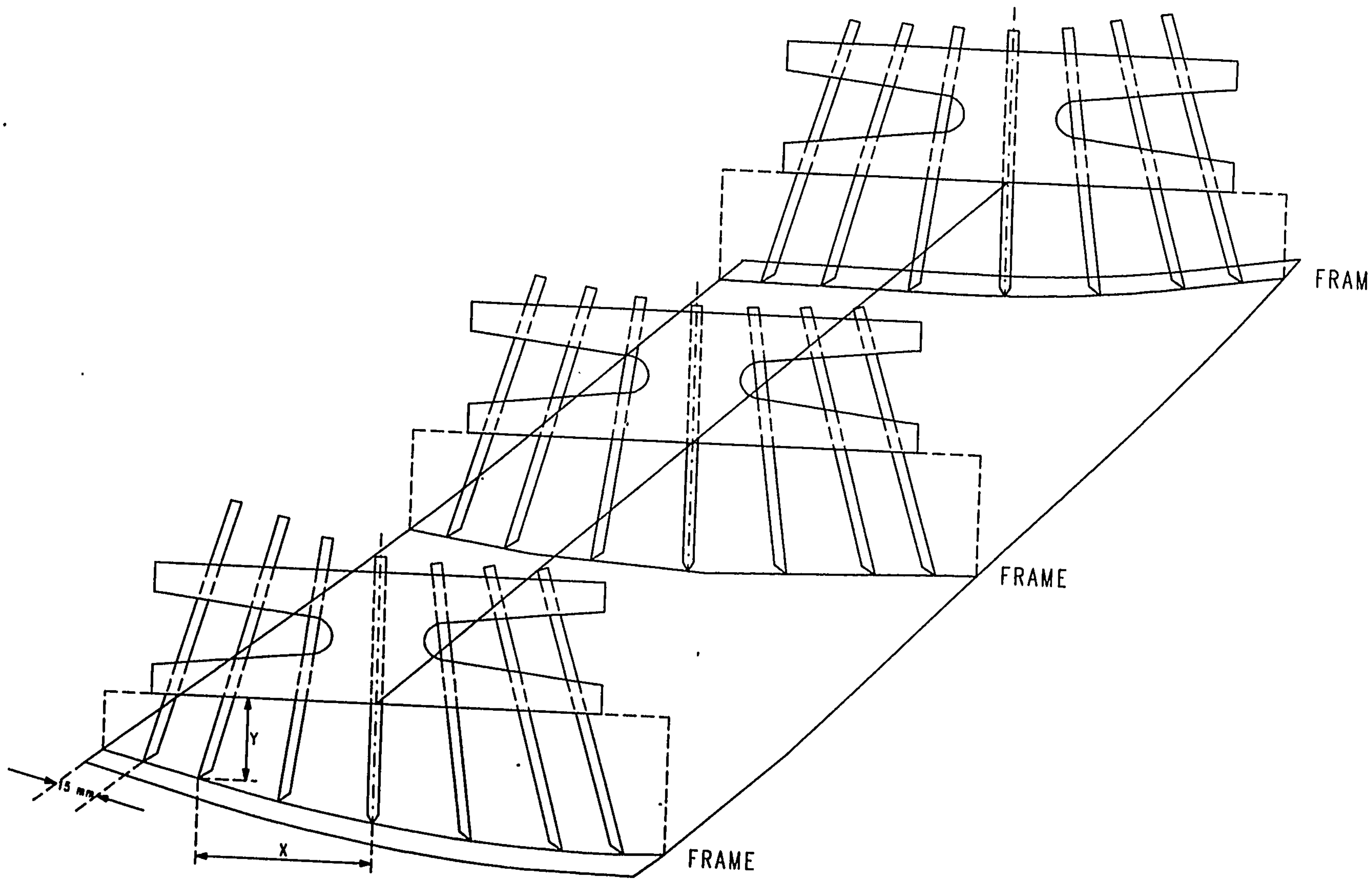


FIG. B.2

APPENDIX 10.2

BOEING COMMERCIAL AIRPLANE GROUP LETTER

Boeing Commercial Airplane G~ap
P.O. Box 3707
Seattle, WA 98124-2207

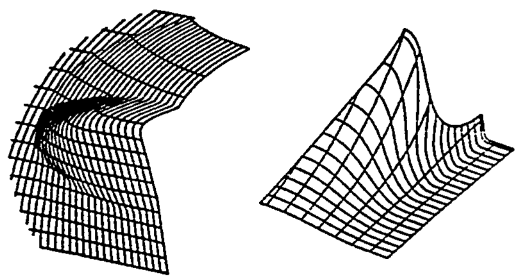
April 29,1991

Mr. Thomas Lamb
805 Cross Gates Blvd.
Slidell, La 70461

Dear Mr. Lamb

This note is a response to your letter dated April 8, 1991. Boeing will not submit a proposal for this project. Information is provided on how the Boeing Commercial Airplane Group lofts and-fairs extreme compound contour surfaces.

BOEING



The above surfaces represent our definition of extreme compound contour. These complex shapes usually begin with crude lofts or with plan, side and cross-section curves and evolve through a series of iterations. The lofting software that we use is a sub-set of CATIA, a CAD\CAM System developed by Dassault Systems in France and marketed by IBM. The lofting techniques that we use can be traced back to R. A. Limingts 1944 book titled ‘Practical Analytic Geometry With Applications To Aircraft". We rely upon a cadre of skilled loftsraen that work closely with designers, aerodynamicists, and manufacturing representatives to produce shapes that meet esthetic, design, performance and producibility criteria.
Our skin panels with compound contour can be sub-divided into 1) sheet which is stretch formed or hammer formed over dies, 2) composite laminates which are formed on lay-up mandrels and 3) wing skins which are formed by shot peening. The closest of these to a hull plate is the wing skin. We develop 2-D flat patterns from three-dimensional wing surfaces by triangulating between point arrays and compensating to achieve closure. We do not have automated shape generation or fairing tools.

Thanks for the ShipCAM3, CAE and vendor information. If I can be of further assistance, please contact me.

Since l

C. Liechty

Carroll Liechty

BOEING 1916 1991 75 YEARS

APPENDIX 10.3

KEY LINE MARKING METHOD FOR CURVED SHELL PANELS

KEY LINE MARKING METHOD FOR CURVED SHELL PANELS”

(REPRODUCED FROM AVONDAL/IHI TECHNOLOGYTRANSFER VOLUME III - MOLD LOFT, PRODUCTION CONTROL, ACCURACY CONTROL)

In order to completely achieve the Shell Jig System in the shipyard, we have adopted the IHI curve shell marking method by means of steel marking tapes.

It is our experience that in producing curve shell assemblies, the following errors can occur:

- errors caused by plate development
- errors caused by heat deformation
- marking errors caused by the N/C punching device
- deformation caused by shrinkage and expansion through the plate bending procedures

Even if these errors are minute for one plate, the accumulated errors will affect the entire assembly.

The use of the girth table is not enough to obtain accurate curved shell, because the girth table indicates distances of structures from centerline of the ship. Therefore, it is impossible to determine what seam position should be the starting point

In order to obtain accurate curved units, the most significant way is to establish two (2) key lines which are perpendicular to each other on the curved shell. SEE FIGURE 1 (VIEW GRAPH NO. ML-37).

This marking method has the following advantage

- accurate cutting of curved shelI erection joints
- higher accuracy in the layout of curved units
  SEE FIGURE 2 (VIEW GRAPH NO. ML-38).

All calculations for this marking system are generated through the SPADES programming system.
SEE FIGURES 3,4 &5 (VIEW GRAPH NOS. ML-39, ML-40, & ML-41).

This information is sent to the Moldloft where the finished marking tape and degree templates are prepared.

A. MARKING METHOD

1. Step No. 1- Marking Procedure of Key Line

a. Using the highest tape at the aft and forward butts, check the material size of each plate and the size of the assembly.

b. Mark the key line points on the shell at the aft and forward butts and at a frame nearest the center of the unit. This frame is called the key Frame.
SEE FIGURE 7 (VIEW GRAPH NO. ML-421.

c. Place the length tape along the three (3) points (A, B & C).

d. Connect points A and B with a thread line. Place the key line template along the key frame at the key line. This procedure will check the longitudinal curvature of the assembly.

2. Step No. 2 - Marking Procedure of the Vertical Lines

a. In order to establish an accurate key frame, the vertical curvature of the assembly must be checked first.
SEE FIGURE 9 (VIEW GRAPH NO. ML-44).

b. With the use of a beam compass and a set of three dimensional lengths obtained through the N/C program (FIGURE 3), mark points A and B horn points C and D.

c. If the cross marks fall off the seam, this will indicate either a bad cut or incorrect curvature.

d. If differences do exist, check the following items:

- clearance between the sehll plate and the jig
- distance between the corners of the starting plate and the jig
- heights of the pins
- loose hanging edge of the shell plate
- recheck the assembly marking tape

3. Step No. 3- Marking Procedure of the Key Frame Line

SEE FIGURE 10 (VIEWGRAPH NO. ML-45)

a. Join points G and F with a thread and put the backset template on the key line to check backset Length and the declevity of the frame.

b. The backset template at this point establishes point H. Point H represents the intersection of the key line and key frame .

c. With another thread, join points F, H and G. By seeing through the threads, visualize a plane through the three points to confirm the key frame. Mark several points on the shell and, by using a wooden batten, create the key frame.

SEE FIGURE 10 (VIEW GRAPH NO. ML-45)

4. Step No. 4- Marking Procedure of Frame Lines and Internal SStructure Lines

SEE FIGURE 11 (VIEW GRAPH NO. ML-46)

a. Taking the height tape, meet the key line mark on the tape to the key line at each frame position. Mark all height points of the internal structures, water lines, and erection seam lines at every frame.

b. Taking the length tape, meet the key frame mark on tie tape to the key frame line. Mark all length points of the internal lines, buttock lines, buttock lines, and erection butts.

c. Using a wooden batten, join all cross mark points to get the frame lines, buttock lines, water lines, internal structure and erection seam lines.

B. CONCLUSION

This concludes the Assembly Marking Method for Curved Shell. At this point, all lines have been re-marked, even if the line had been already marked by the N/C burning machine. Good results horn this marking system are being realized as the Exxon ship is being erected. We are already experiencing better alignment of internals across units with less stock required on the units.

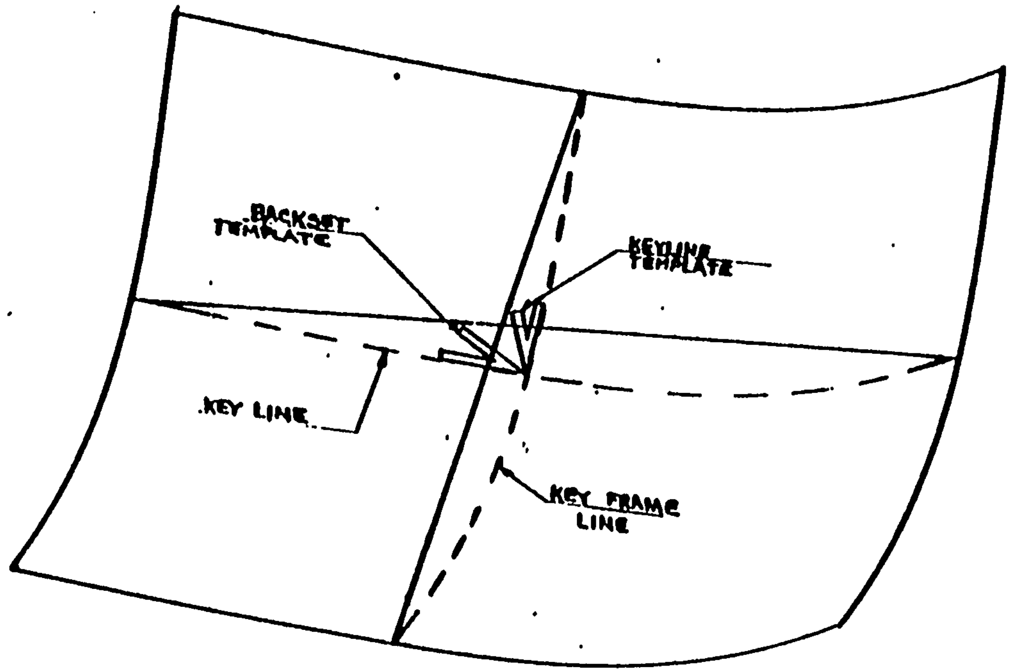
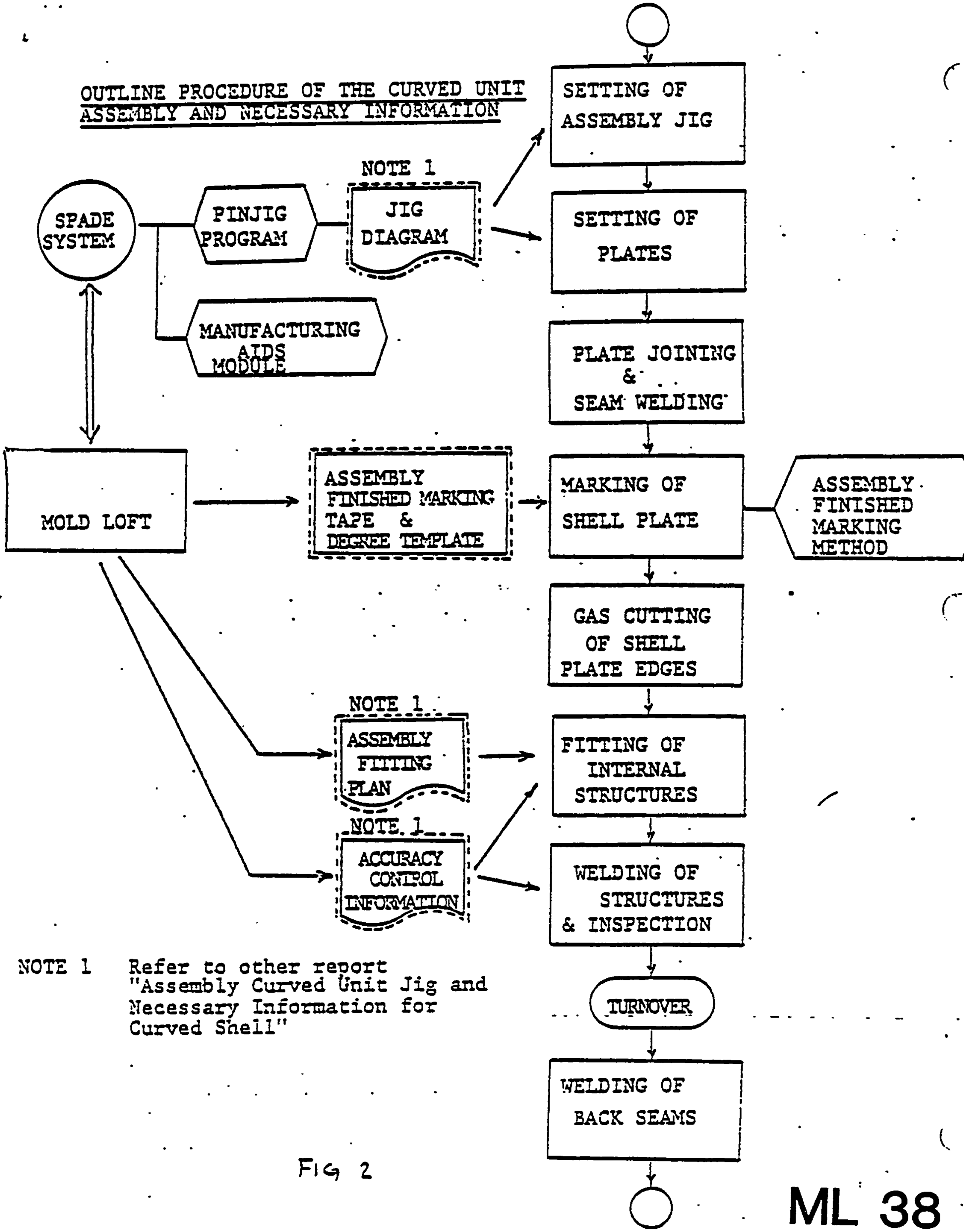


FIG. 1

OUTLINE PROCEDURE OF THE CURVED UNIT ASSEMBLY AND NECESSARY INFORMATION



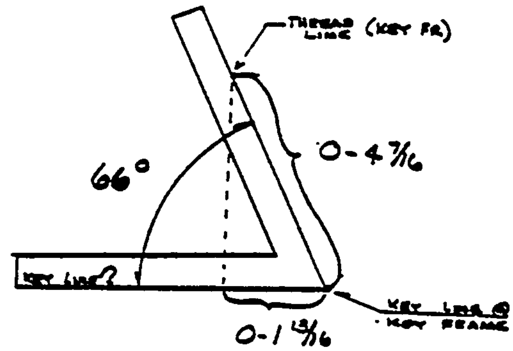
NOTE 1 Refer to other report "Assembly Curved Unit Jig and Necessary Information for Curved Shell"

FIG 2

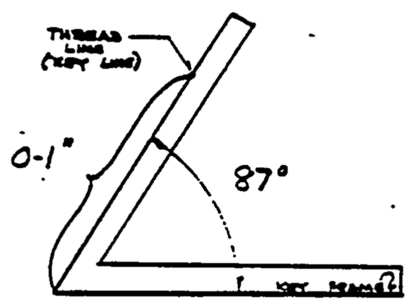
ML 38

JOB C1-15 UNIT 48

Back Set Template



Key Line Template



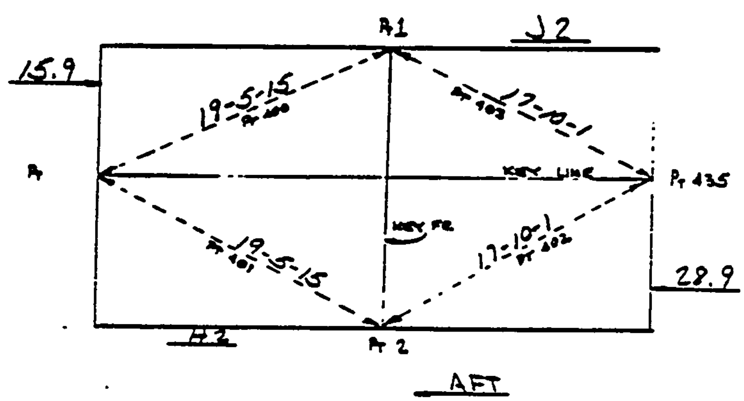


FIG 3

ML 3

JOB C1-15
TAPE 31
DATE 9-13-82
NAME GIL HEBERT

TABLE LENGTH

UNIT 48

	15.9	16	17	18	19	20	21	KEY 22 FRAME	23	24	25	26	27	28	28.9
J2	19-5-1	17-3-14	14-5-7	11-6-14	8-8-4	5-9-9	2-10-13	0	2-10-13	5-9-9	8-8-5	11-6-15	14-5-8	17-4-0	18-8-1
24" 3" FLAT	19-3-13	17-2-13	14-4-9	11-6-4	8-7-13	5-9-4	2-10-11	0	2-10-11	5-9-6	8-8-1	11-6-10	14-5-2	17-3-9	18-7-9
KEY LINE	18-5-5	16-5-4	13-8-5	10-11-8	8-2-10	5-5-11	2-8-14	0	2-8-13	5-5-10	8-2-6	10-11-2	13-7-13	16-4-8	17-7-12
J1	18-6-10	16-6-11	13-9-15	11-1-0	8-3-15	5-6-12	2-9-7	0	2-9-8	5-7-2	8-4-12	11-2-9	14-0-6	16-10-4	18-2-1
H2	17-11-15	16-0-7	13-4-7	10-8-7	8-0-7	5-4-6	2-8-4	0	2-8-5	5-4-12	8-1-4	10-9-14	13-6-10	16-3-6	17-6-11

FIG 4

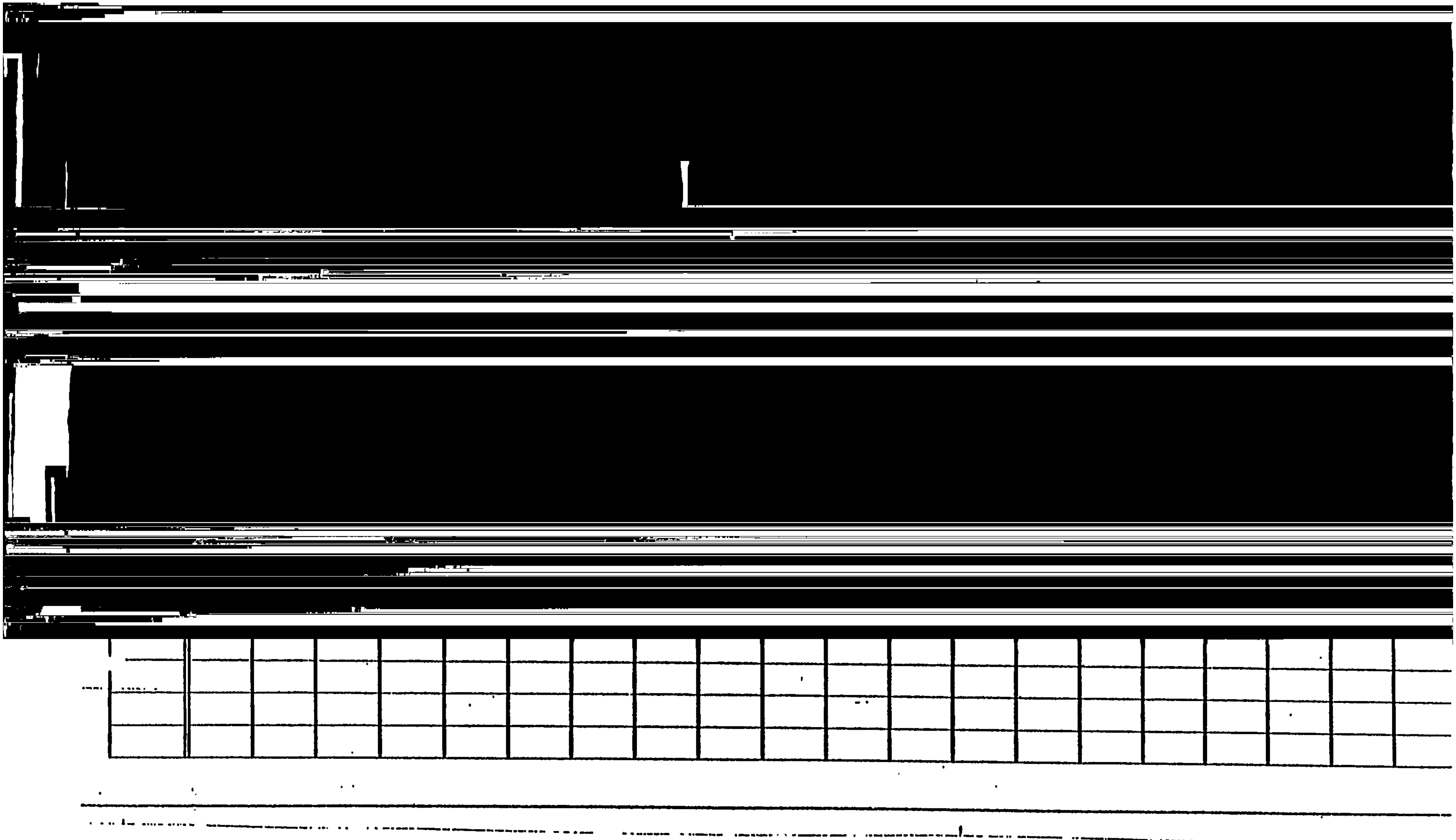


FIG 5

ML 41

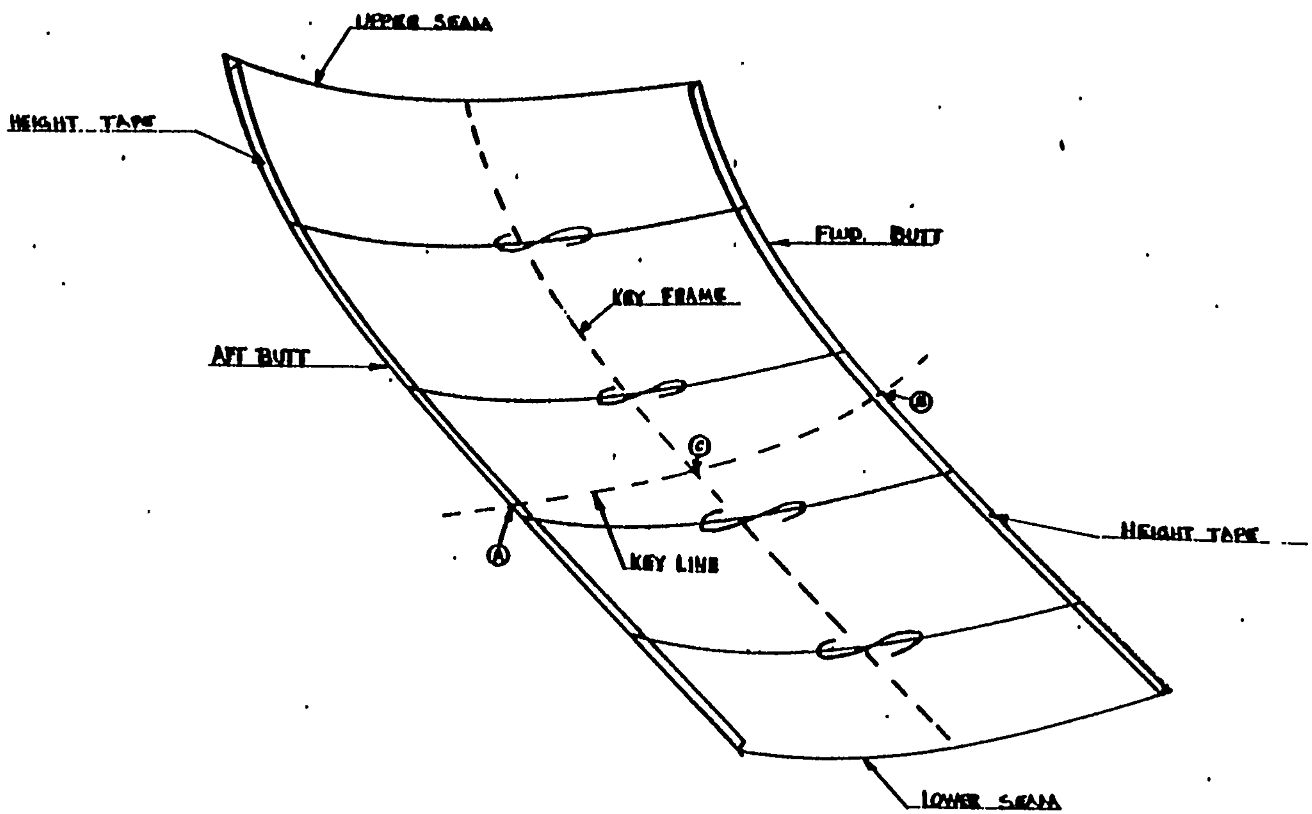

UPPER SEAM
HEIGHT TAPE
FWD. BUTT
KEY FRAME
AFT BUTT
KEY LINE
HEIGHT TAPE
LOWER SEAM

FIG. 7

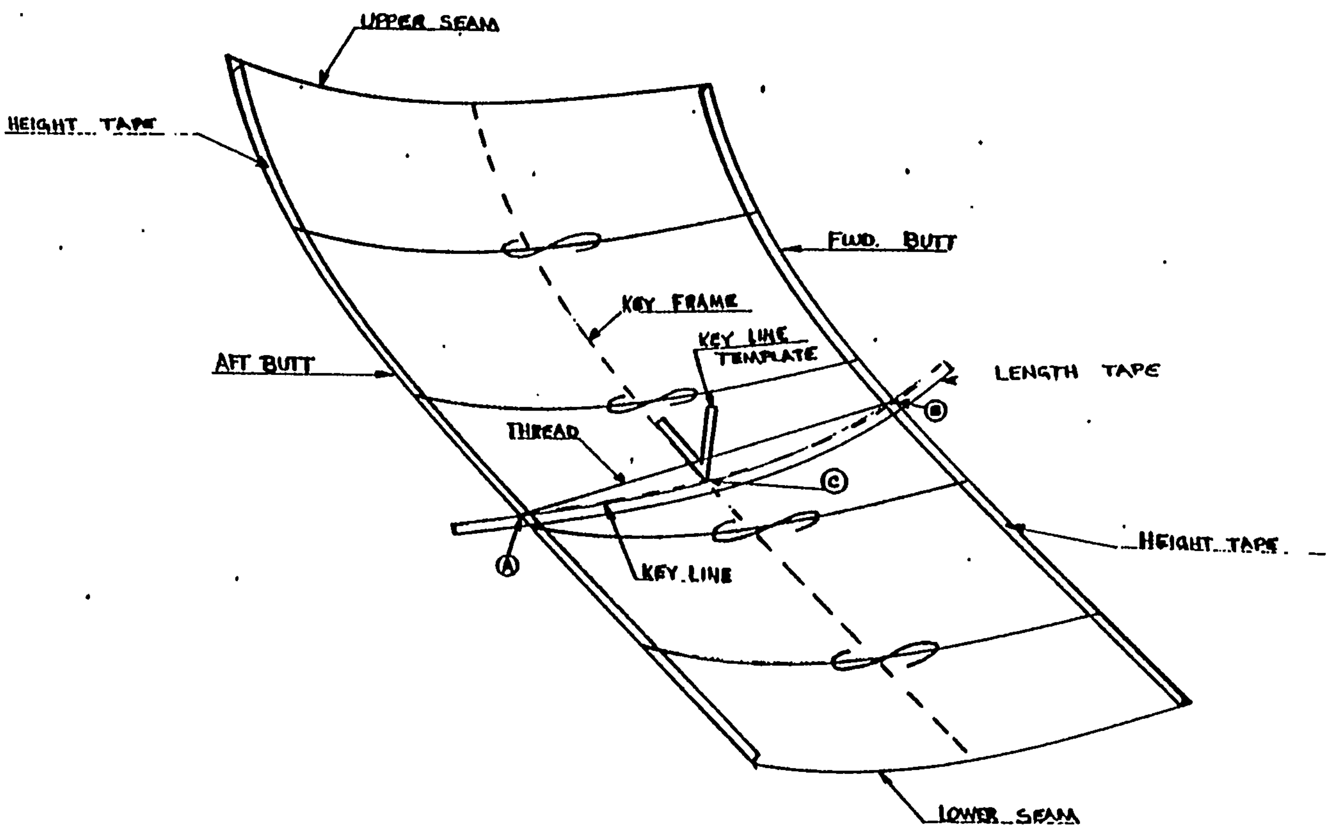

UPPER SEAM
HEIGHT TAPE
FWD. BUTT
KEY FRAME
KEY LINE TEMPLATE
AFT BUTT
LENGTH TAPE
THREAD
B
C
A
KEY LINE
HEIGHT TAPE
LOWER SEAM

FIG 8

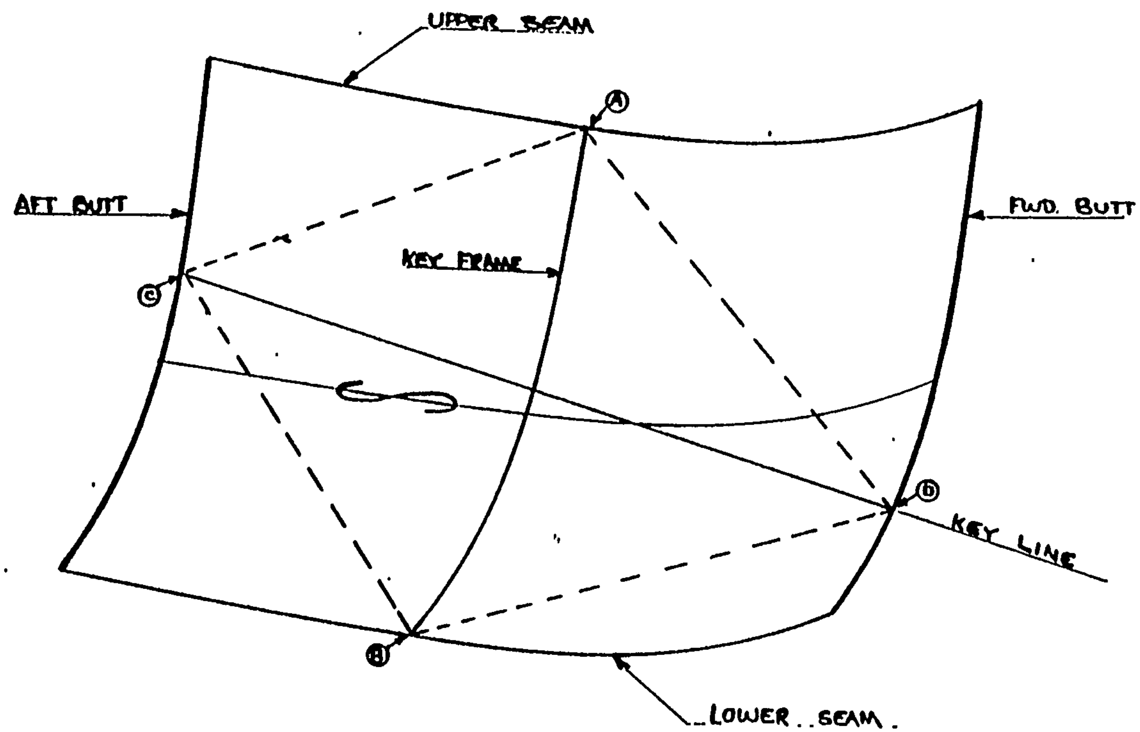

UPPER SEAM
AFT BUTT
FWD. BUTT
KEY FRAME
KEY LINE
LOWER SEAM
A
B
C
D

FIG 9

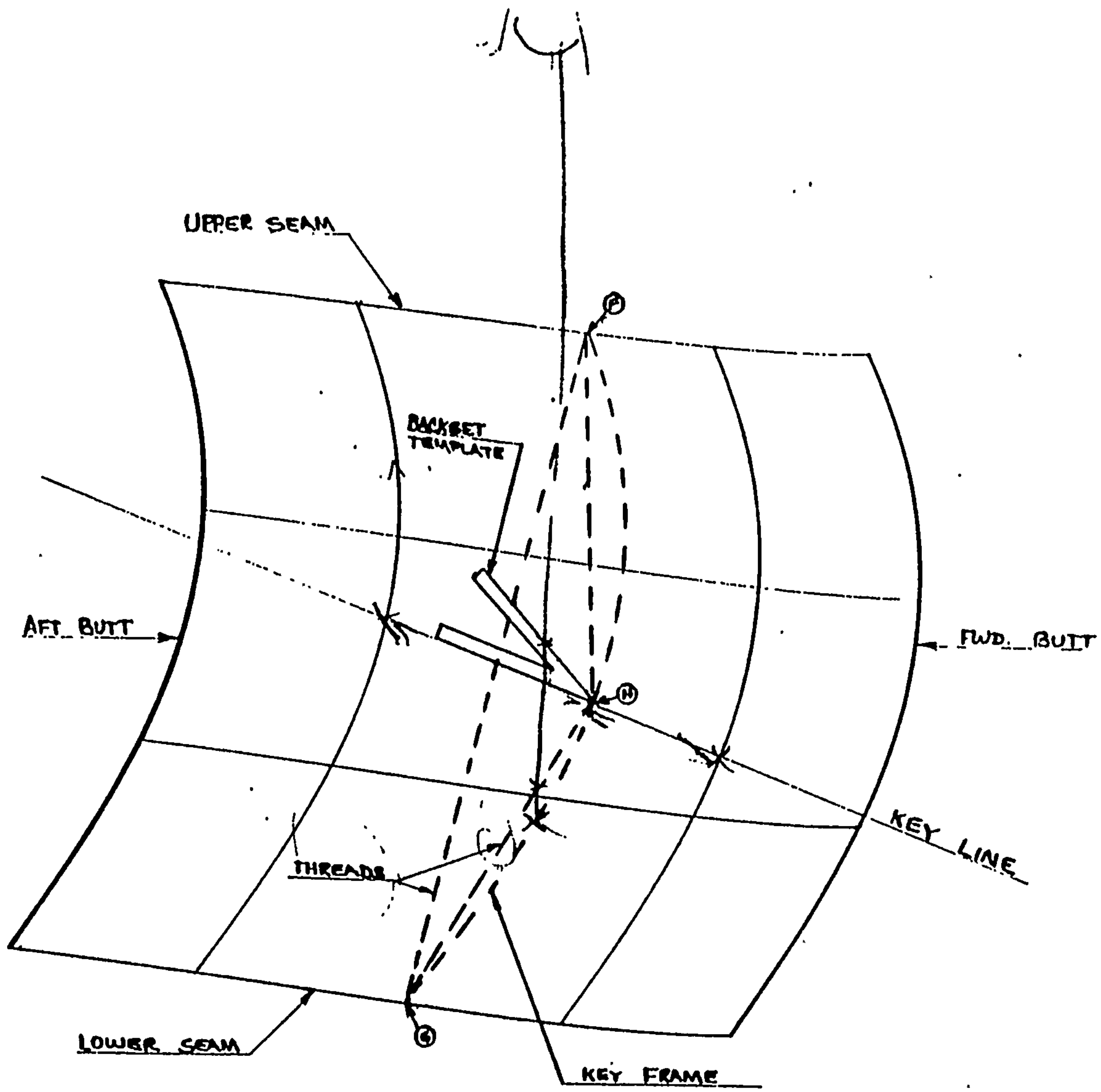
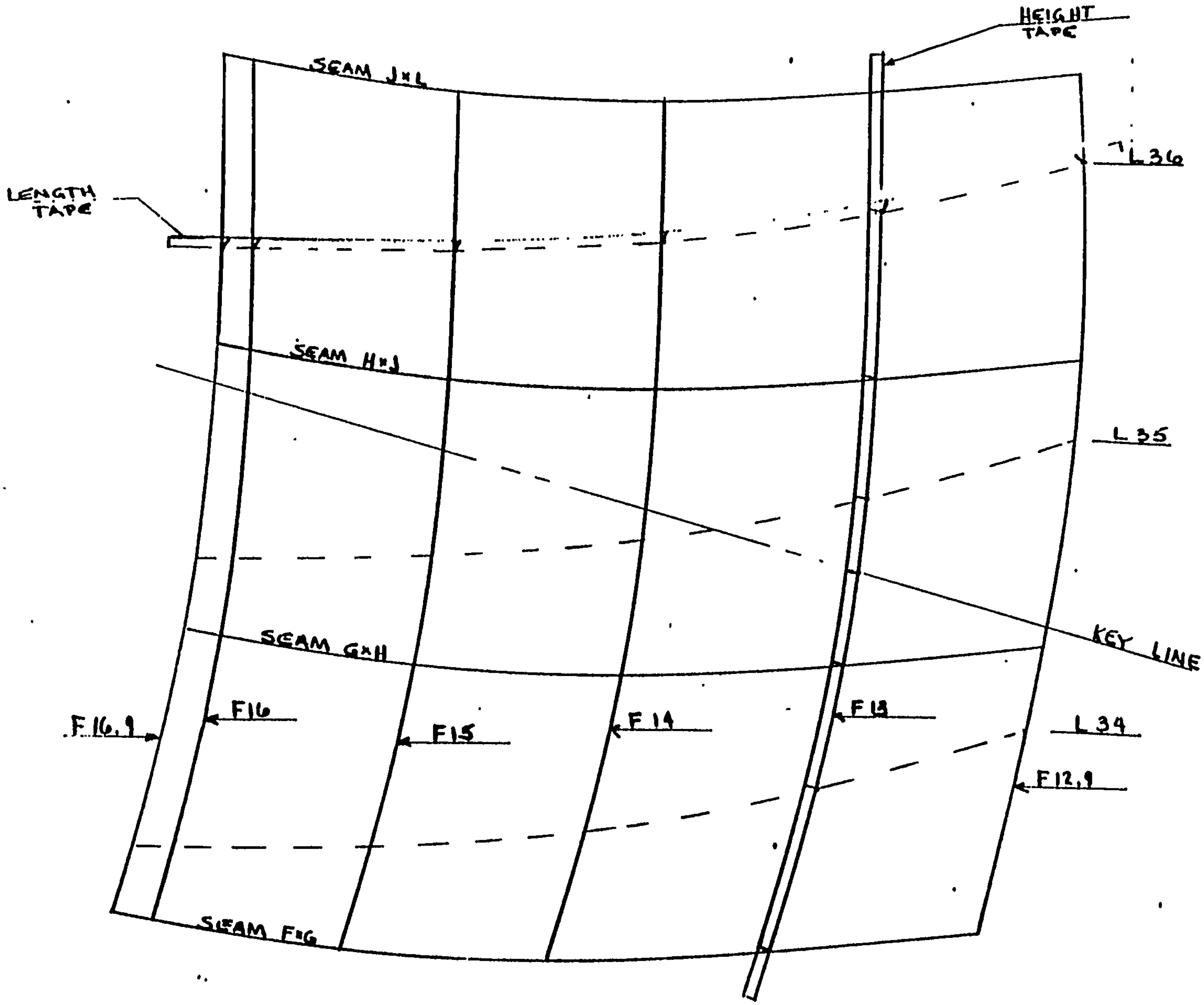

UPPER SEAM
BACKSET TEMPLATE
AFT BUTT
FWD. BUTT
KEY LINE
THREADS
LOWER SEAM
KEY FRAME

FIG 10

ML 45



HEIGHT TAPE
SEAM J×L
L 36
LENGTH TAPE
SEAM H×J
L 35
KEY LINE
SEAM G×H
F16.9
F16
F15
F14
F13
L 34
F12.9
SEAM F×G

Fig. 11

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